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GUIDELINES FOR DELINEATION OF WELLHEAD PROTECTION AREAS

OFFICE OF WATER
OFFICE OF GROUND-WATER PROTECTION
U.S. ENVIRONMENTAL PROTECTION AGENCY

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FOREWORD

These guidelines are provided as technical assistance to State and local governments in their efforts to protect ground-water resources supplying public wells used for drinking water. The document is one in a continuing series of publications on the hydrogeologic aspects of ground-water protection, prepared in response to the 1986 Amendments to the Safe Drinking Water Act. Policies regarding applications by States for financial support are addressed in separate grant guidance and application documents. Additional information on the Wellhead Protection Program is available from the Office of Ground-Water Protection in Washington, D.C., and from the ten EPA Regions.

EXECUTIVE SUMMARY

The Amendments to the Safe Drinking Water Act (SDWA), which were passed in June 1986, established the first nationwide program to protect ground-water resources used for public water supplies from a wide range of potential threats. Unlike previous Federal programs, which have tended to focus on individual contaminant sources, this new effort approaches the assessment and management of ground-water quality from a more comprehensive perspective. The SDWA seeks to accomplish this goal by the establishment of State Wellhead Protection (WHP) Programs which "protect wellhead areas within their jurisdiction from contaminants which may have any adverse effect on the health of persons."

One of the major elements of WHP is the determination of zones within which contaminant source assessment and management will be addressed. These zones, denoted as Wellhead Protection Areas (WHPA's), are defined in the SDWA as "the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield." Hence, the law establishes the concept of protecting some of the recharge areas to these points of public drinking water withdrawal. The States are given flexibility in determining appropriate operational approaches to WHPA delineation. The Environmental Protection Agency (EPA), in addition, is required by the SDWA to release technical guidance on the hydrogeologic aspects of this task. These **Guidelines for Delineation of Wellhead Protection Areas** are provided to meet this need. Apart from this requirement, issuance of this guidance does not affect or inhibit EPA regulatory programs.

WHPA delineation policy is generally based upon the analysis of criteria, criteria thresholds, and delineation methods. The criteria and criteria thresholds define the general technical basis of the WHPA. The WHPA delineation methods are used to translate or apply these criteria, to develop on-the-ground or on-the-map WHPA boundaries. In preparation for criteria and method selection, most States will assess the availability of hydrogeologic data and the institutional capability of the State to perform such technical assessments.

HYDROGEOLOGIC AND CONTAMINANT CONTROLS OVER WHPA DELINEATION

These delineation guidelines provide a discussion of the basic concepts of ground-water flow and contaminant transport, as they apply to the task of WHPA delineation. Differences among the major aquifer types are emphasized.

Approximately half the U.S. population is dependent on ground-water sources--wells and springs--for its domestic water. Though springs are occasionally used for water supplies, exploitation of ground water normally requires the drilling and installation of wells or well fields. Under natural conditions, ground water is in equilibrium and flows from areas of higher head to areas of lower head. Ground-water pumping or discharge alters the natural equilibrium and causes the lowering of water levels around the pumping well. This effect, called drawdown, affects an area referred to as the zone of influence (ZOI) of the well. This expression is generally synonymous with the commonly encountered term "cone of depression." Part of the ZOI is contained within the zone of contribution (ZOC), which includes all areas that recharge or contribute water to the well or well field. The guidance notes that both technical and nontechnical specialists commonly (though incorrectly) assume that the ZOI is always completely contained within the ZOC. Understanding the differences between these concepts is essential to fostering more precise WHPA delineation.

The concept of a WHPA can be applied to a variety of aquifer types under both confined and unconfined conditions. Unconfined aquifers, also known as "water-table aquifers," are in direct hydrogeologic connection with the surface, and hence are generally more vulnerable to contaminants originating at or near the surface than confined aquifers. Confined aquifers, sometimes known as "artesian aquifers," occur beneath less permeable materials and are under pressure conditions greater than atmospheric. Despite this generally less vulnerable basic condition, confined aquifers are susceptible to contamination from a variety of factors--the relative difference in head between the aquifer and other aquifers, natural or human-induced breaks in confinement such as fault zones or abandoned and corroded well casings, and the physical conditions of the confining unit itself. The guidance provides technical information to help States evaluate the extent of specific WHPA's needed for wells under confined conditions. More tailored WHPA techniques for conduit karst, fractured bedrock, and other "exceptions" to the basic aquifer types are also noted.

The delineation guidelines assume that WHPA delineation and protection will be targetted to three general threats. The first is the direct introduction of contaminants to the area immediately contiguous to the well through improper casing, road runoff, spills, and accidents. A second basic threat is from microbial contaminants such as bacteria and viruses. The third major threat is the broad range of chemical contaminants, including inorganic and naturally occurring or synthetically-derived organic chemicals. The transport characteristics of these classes of contaminants are reviewed briefly in the guidance document.

WHPA DELINEATION CRITERIA

There are several operational goals the States may use to meet the delineation elements of the statutory goals for WHP. Three of these are: provide a **remedial action zone** to protect wells from unexpected contaminant release; provide an **attenuation zone** to bring the concentrations of specific contaminants to desired levels by the time they reach the wellhead; and provide a **well-field management zone** in all or part of a well or well field's existing or potential recharge area. Some conceptual standard is needed, however, to meet these goals.

The conceptual standards on which WHPA delineation may be based are referred to in this document as **criteria.** They may include distance, drawdown, travel time, flow system boundaries, and the capacity of the aquifer to assimilate contaminants. Choice of the criteria to be applied will likely be based on both technical and nontechnical considerations.

The technical merits of a criterion depend on the degree to which it incorporates physical processes affecting ground-water flow and contaminant transport. Nontechnical considerations include a State's institutional capabilities for implementing a program, together with economic and demographic realities in the State. After selection of criteria for WHPA delineation, appropriate thresholds must be chosen. These are values that represent the limits above or below which a criterion will cease to provide the desired degree of protection.

A distance criterion defines the WHPA by a radius or dimension measured from a pumping well to encompass the area of concern. A drawdown criterion defines the WHPA as the area around the pumping well in which the water table (in an unconfined aquifer) or the potentiometric surface (in a confined aquifer) is lowered by the pumping; this involves mapping all or part of the zone of influence. The time of travel (TOT) criteria bases the

WHPA boundary on the time required for contaminants to reach the water supply. A flow boundaries criterion incorporates the known locations of ground-water divides and other physical or hydrologic features that control ground-water movement. The assimilative capacity criterion is based on the subsurface formation's capacity to dilute or otherwise attenuate contaminant concentrations to acceptable levels before they reach public drinking-water wells.

Each of the criteria has advantages and disadvantages in meeting these goals, depending largely on the hydrogeologic settings within a State, as well as the administrative and technical resources available. Selecting appropriate criteria thresholds will be another key decision point, although it will be done in conjunction with establishing the management elements of the WHP.

WHPA DELINEATION METHODS

Following selection of WHPA delineation criteria, it is necessary to choose the specific methods for mapping the selected criteria. Six methods have been identified as having been used in WHPA delineations. These are, in increasing order of cost and sophistication: arbitrary and calculated fixed radii, simplified variable shapes, analytical methods, hydrogeologic mapping, and numerical flow/transport models. They range from simple techniques to highly complex and comprehensive ones.

The arbitrary fixed radius method involves circumscribing a zone around the water supply that is based on a distance criterion threshold. Though simple and inexpensive, this method may tend to over-protect or under-protect. A significant improvement over no delineation, the method is often used for microbial protection, or in the early phases of a WHP Program for chemical contaminants.

The calculated fixed radius method applies an analytical equation to calculate the radius of a circular WHPA based on a time-of-travel criterion. Though still relatively simple and inexpensive to apply, this method provides more accuracy, depending on site conditions.

Simplified variable shapes are standard outlines of WHPA's, generated using analytical models, and generally based on a combination of flow boundary and time-of-travel criteria. The appropriate shapes are then chosen to match or approximate conditions encountered at specific wellheads, well fields, and springs. This is another inexpensive yet somewhat more accurate technique.

Analytical methods may be used to define ground-water flow boundaries and contaminant transport dynamics through the application of empirically derived equations. This is perhaps the most commonly used method where greater precision is needed.

Hydrogeologic mapping can be used to map flow boundaries and to implement other criteria through use of geological, geomorphic, geophysical, and dye tracing methods. The method is particularly appropriate in some types of aquifers.

Numerical models use mathematical approximations of ground-water flow and/or contaminant transport equations that can take into account a variety of hydrogeologic and contamination conditions. These models offer possibly the most accurate delineations, though at considerable cost.

Comparisons of the results of specific methods in "case study" applications can be used to evaluate and then choose WHPA delineation techniques. In such comparative analyses, the output from more expensive, complex methods is generally compared with the results from less expensive, simpler techniques to determine the cost and benefit tradeoffs in given hydrogeologic settings. These case analyses will also be useful for evaluating, on a generic basis, the spatial extent of different WHPA's based on different criteria and criteria thresholds. Such information could be very useful in the early phases of a State WHP Program, to begin the assessment of potential contamination threats to public water supplies.

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CHAPTER 1

INTRODUCTION

Nearly half the population in the United States uses wells or springs to obtain drinking water (U.S. Geological Survey, 1984). Improper management of contamination sources resulting from human activities often causes degradation of these supplies. One solution to this problem is to prevent contaminated ground water from reaching wells and springs by establishing areas of protection around them.

A new provision in the 1986 Amendments to the Safe Drinking Water Act (SDWA) is the Wellhead Protection (WHP) Program. This program is designed to assist States in protecting areas surrounding wells within their jurisdiction against contaminants that may have adverse effects on human health (SDWA, Section 1428(a)). The Amendments mandated that, among other provisions, the U.S. Environmental Protection Agency (EPA) Administrator issue technical guidance that States may use in determining the extent of such areas of protection (Section 1428(e)). This document has been prepared to furnish such guidance. Another document, **Guidance for Applicants for State WHP Program Assistance Funds**, is also available to aid States and Territories in applying for program support.

1.1 LEGISLATIVE AUTHORITY

The 1986 Amendments to the SDWA authorized two new provisions for ground-water protection. These were the WHP Program and the Sole Source Aquifer (SSA) Demonstration Program. Both are designed to support the development of State and local efforts to protect ground-water resources. The statutory language creating these programs is in Section 1427 (SSA Demonstration Program) and Section 1428 (State Programs to Establish Wellhead Protection Areas). The intent of Section 1428 is to establish a State program that adequately protects the wellhead areas of all public water systems from contaminants that may have adverse human health effects.

The SDWA incorporates the fundamental definition of a WHPA in Subsection 1428(e):

(e) DEFINITION OF WELLHEAD PROTECTION AREA--As used in this section, the term 'wellhead protection area' means the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield. The extent of a wellhead protection area, within a State, necessary to provide protection from contaminants which may have any adverse effect on the health of persons is to be determined by the State in the program submitted under subsection (a). Not later than 1 year after the enactment of the Safe Drinking Water Act Amendments of 1986, the Administrator shall issue technical guidance which States may use in making such determinations. Such guidance may reflect such factors as the radius of influence around a well or wellfield, the depth of drawdown of the water table by such well or wellfield at any given point, the time or rate of travel of various contaminants in various hydrologic conditions, distance from the well or wellfield, or other factors affecting the likelihood of contaminants reaching the well or wellfield, taking into account available engineering pump tests or comparable data, field reconnaissance, topographic information, and the geology of the formation in which the well or wellfield is located.

The statute furthermore defines a WHP Program as one that incorporates the following elements:

- Duties of State and local agencies and public water supply systems in implementing the program
- Determination of WHPA's for each public well or well field
- Identification of all potential anthropogenic sources within the protection area
- A program that contains, as appropriate: technical assistance, financial assistance, implementation of control measures, education, training, and demonstration projects to protect wellhead areas from contaminants
- Contingency plans for alternative water supplies in cases of contamination
- Siting considerations for all new wells
- Public participation.

This program must be submitted to the Administrator of EPA within 3 years after enactment. States are expected to make every reasonable effort to implement this program within 2 years after it has been submitted to the Administrator. The only impact on a State for failing to participate in the WHP Program, however, is the loss of grant funds. EPA is not authorized to establish a WHP Program in a State that does not choose to participate.

1.2 PURPOSE AND SCOPE OF DOCUMENT

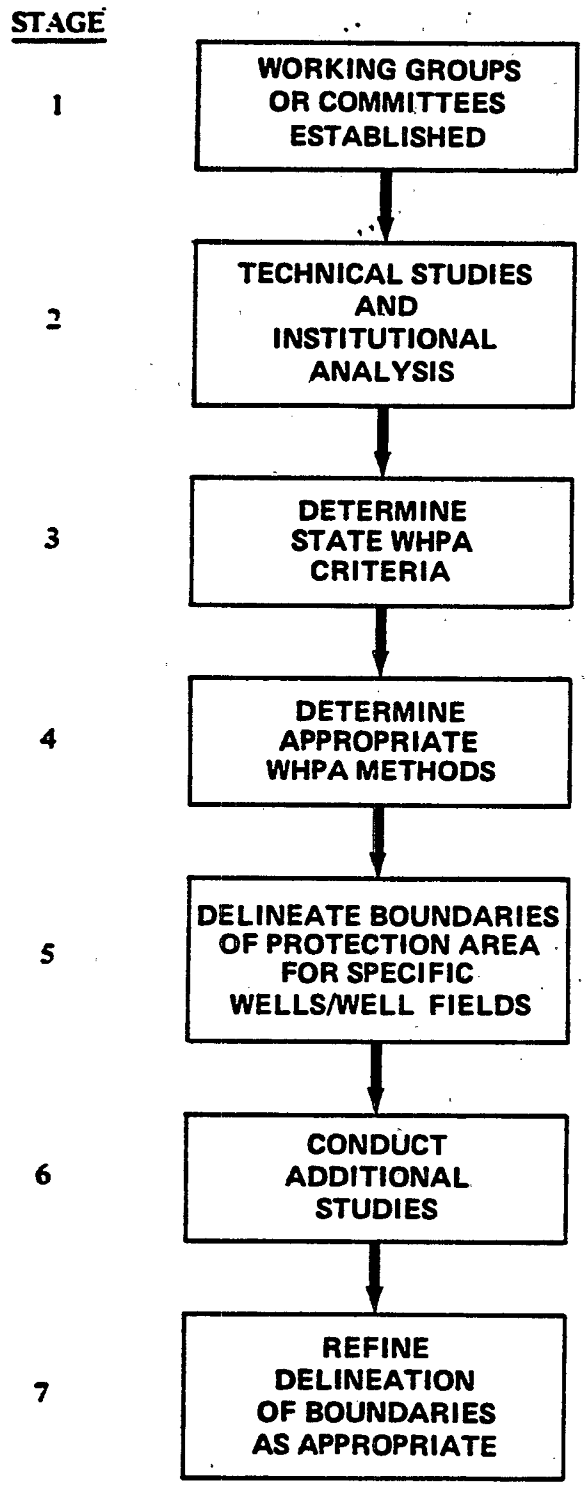
Instituting WHP in the United States will present two major challenges. First will be to resolve successfully the technical problems of delineating meaningful protection areas to prevent ground-water contamination. The second will be to resolve the vast complex of management problems that will accompany attempts to implement the WHPA's. States will face major institutional hurdles, for example, in controlling industrial, commercial, and agricultural activity and land usage within the delineated WHPA's. The scope of this document is to provide general guidance in solving the initial problems of actually delineating the protection areas. The document does not prescribe specific mechanisms or approaches that must be strictly followed. Instead, the document describes a variety of technical approaches, from the simple to the sophisticated, that may be used singly or in combinations. The issuance of this guidance, in and of itself, furthermore does not affect or inhibit Agency regulatory programs.

Ground-water protection is primarily a State responsibility. Accordingly, EPA intends to ensure that States and localities have flexibility in developing their programs, while ensuring that the goals and objectives of the law are met. EPA expects that there will be several stages in a State program for WHPA delineation, shown in general terms in Figure 1-1. Initially, the States will probably establish technical committees or work groups to review relevant technical materials (including this delineation guidelines document) and conditions within the State. After analysis by program personnel, often including "test case" applications, "criteria" and "methods" will be adopted, and the actual delineation and mapping of the areas will commence.

Determination of State WHPA criteria and appropriate WHPA methods (Stages 3 and 4 in Figure 1-1) are the two major topics covered in this guidance document. **Criteria** refer to the primary delineation factors mentioned in the statute (Subsection 1428(e)) (e.g., "radius of influence, depth of drawdown, time or rate of travel"). The term criteria is used here because these factors can be used as conceptual standards on which to base WHPA delineations. The **methods** are the techniques that can be used to map the WHPA's. These methods range from simple "cookie-cutter" approaches to complex computer models.

Only a few States have been active in wellhead protection. However, numerous European nations have been involved in such programs (Van Waegeningh, 1985). Information based on their experiences has been incorporated into this document.

Figure 1-1
General Approach to State WHPA Delineation



EPA expects that delineation of WHPA's will be implemented so as to protect wells from three general categories of threats--the direct introduction of contaminants through and around the well casing, microbial contaminants, and chemical contaminants. The immediate vicinity of the well or well field is a primary area to be protected from accidental spills, road runoff, and similar incidents. The management of this area may include standards for well casing, grouting, housing, surface grading, buffer zones, and well abandonment procedures. Microbial contamination, especially from bacteria and viruses, is of significant concern, since micro-organisms may persist in drinking water even after treatment and delivery to consumers.

An important element of the amended SDWA, however, is to provide protection from the broader range of threats to ground-water quality posed by a variety of chemical contaminants. While a few hundred feet of buffer zoning is usually adequate to address microbial threats, many toxic chemicals persist for long time periods and may travel great distances in the subsurface environment. This constitutes the major technical and administrative challenge of the WHP programs. Addressing these threats, particularly the third one, should greatly reduce the incidence of well contamination in the United States.

1.3 EPA'S IMPLEMENTATION APPROACH

The SDWA provisions represent a significant change in the roles and interrelationships of Federal, State, and local governments in ground-water protection. For the first time there is statutory basis at the Federal level for protecting ground-water resources, rather than efforts aimed at controlling specific contaminants or contamination sources. The programs will foster new approaches to resource assessment and protection, and support the State's overall ground-water protection activities. EPA's goals in implementing the WHP Program are to:

- Meet the goals of the statute
- Recognize the diversity of hydrogeologic settings and sources of contamination
- Maximize State creativity and flexibility in program design and implementation
- Be sensitive to concerns regarding Federal involvement in the related areas of land use and water allocation

- Assist States in achieving comprehensive ground-water protection through coordination with State ground-water protection plans and strategies, thus ensuring safe public water supplies.

The Agency's approach during development of these and related guidances has been to encourage the active participation of those who will implement WHP Programs, and of those who will be affected. This has been accomplished by the formation of technical committees, comprising State representatives, academic specialists, and EPA Headquarters and regional staff.

A technical committee on the hydrogeologic aspects of WHP met four times from September 1986 through April 1987. It reviewed proposed criteria and methods for WHPA delineation and made numerous recommendations that were used in subsequent revisions of the draft guidelines. In addition, a 2-day workshop, attended by more than 50 leading technical and policy specialists and State and local officials, was held in January 1987 in Bethesda, Maryland. Detailed presentations of the proposed criteria and methods were followed by group discussions of specific topics in which the participation of all attendees was encouraged. Most of the recommendations and issues raised by the discussion groups were incorporated in subsequent drafts of this guidance document.

EPA established two other technical committees on WHP--one on the grants and financial aspects of the program and the second on the management and control aspects. As a result of their efforts, a series of documents will be available to help the States in developing and implementing WHP, as well as in applying for financial assistance from EPA. Technical specialists involved with the hydrogeologic aspects of WHP delineation must consult the relevant technical section of the "grant guidance" package for insights into EPA's approach for determining program "adequacy" under the SDWA. These requirements are outlined in Sections IV and V of the **Guidance for Applicants for State WHP Program Assistance Funds,** a document available from the Office of Ground-Water Protection in EPA Headquarters and the Regions.

1.4 ORGANIZATION OF DOCUMENT

The main body of this guidance document provides a concise review of WHPA delineation issues. Supporting appendices contain background technical information and examine relevant case studies.

Chapter 2 of this guidance provides basic information on hydrogeologic and contaminant controls over ground-water flow and contaminant transport, as these relate to WHPA delineation. Chapter 3 presents criteria that can be used to establish conceptually the extent of a WHPA; it also provides guidance in the process of selecting a criterion. Chapter 4 identifies the methods available for delineating WHPA's and discusses advantages and disadvantages of each method. Chapter 5 provides a general approach to the WHPA delineation process and examples of criteria and method selections.

Appendix A provides background information on several WHP efforts in the United States and Europe. Appendix B depicts several case studies where the specific criteria and methods are applied, and the resulting WHPA delineations shown. A glossary defines both common hydrogeologic terms and definitions specific to the subject of WHPA delineation.

CHAPTER 2

HYDROGEOLOGIC AND CONTAMINANT CONTROLS OVER WHPA DELINEATION

This chapter provides general information on basic hydrogeologic principles governing ground-water flow under natural and pumping conditions, as well as information on contaminant transport and its relevance to the delineation of wellhead protection areas (WHPA's). For the sake of simplicity, the early discussion in this chapter focuses on flow through porous media under unconfined conditions.

For more elaborate discussion of ground-water flow and contaminant transport, readers may refer to textbooks by Bear (1979), Bouwer (1978), DeWiest (1965), Driscoll (1986), Fetter (1980), Freeze and Cherry (1979), and Todd (1980). Other references by Fried (1975), Matthess, et al. (1981), and Yates, et al. (1984) focus on contaminant transport.

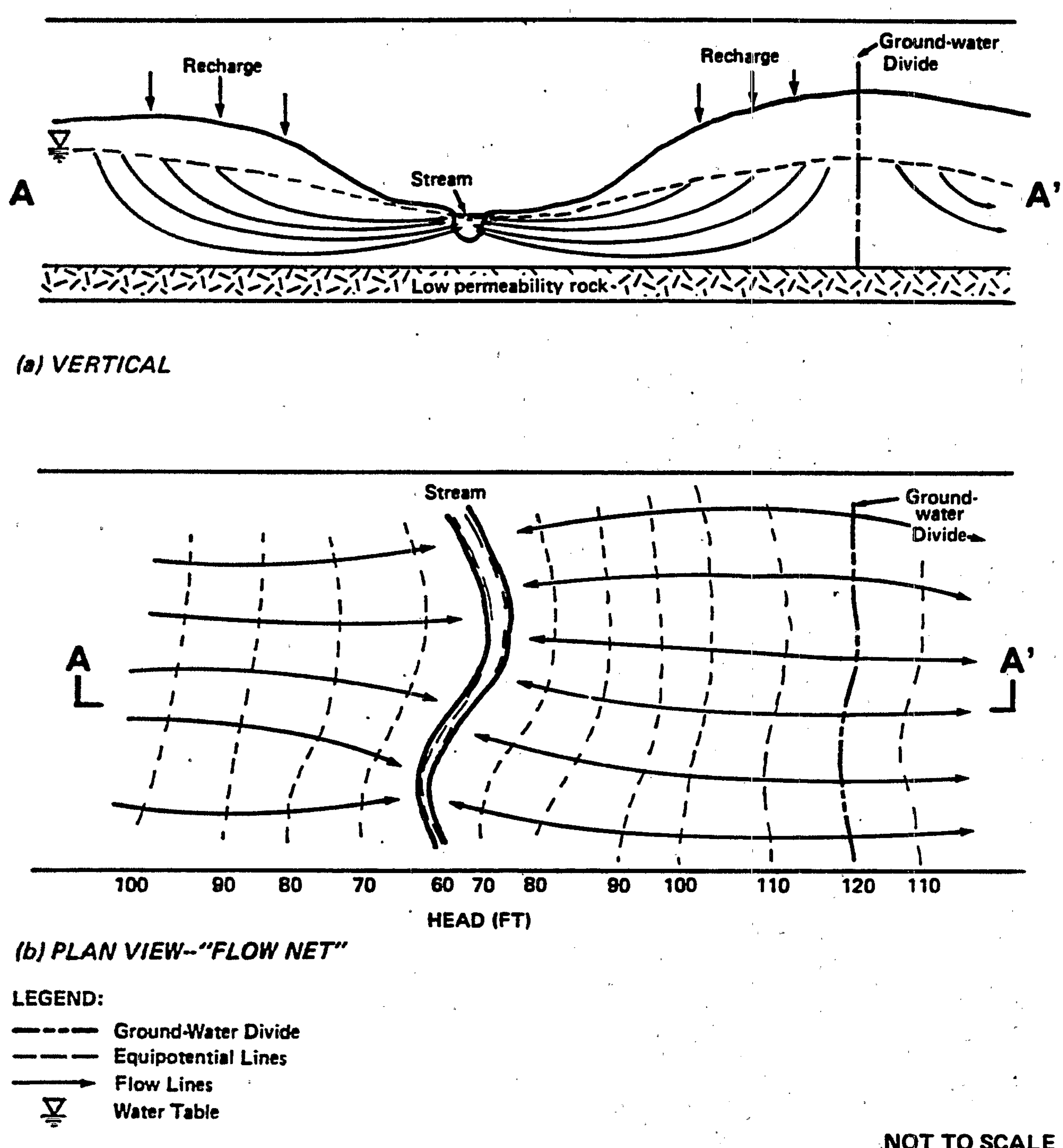
2.1 BASICS OF GROUND-WATER FLOW SYSTEMS

2.1.1 Natural Flow System

Under natural conditions, an aquifer is in a state of dynamic equilibrium. That is, the total recharge to the aquifer is equal to the total discharge, with no change over time in the volume of water stored in the aquifer (Fetter, 1980). The motion of ground water through an aquifer is controlled by differences in energy levels. Ground water moves from areas of higher energy to areas of lower energy in order to reach or maintain a state of equilibrium.

In 1738, Bernoulli developed a fundamental equation that expresses the underlying concept governing ground-water flow. He proved that the "total head" (h) of a unit volume of fluid at a location is equivalent to the sum of the "pressure head" and the "elevation head." This concept introduced the idea that if the total heads at two points in an aquifer differ, ground-water flow will occur from the high-head point to the low-head point. For example, as illustrated in Figure 2-1 for a stream valley system, ground-water flow would occur from the ground-water divide (high head) to the stream (low head). The "equipotential lines" shown in the figure represent lines along which the total head is constant. The "flow lines" represent the paths that ground water would follow under a state of equilibrium. The velocity at which ground water would move through a porous media aquifer can be determined by the following relationship

Figure 2-1
Ground-water Flow System (Stream Valley) Under Natural Conditions



SOURCE: Modified from Driscoll, 1986

$$v = \frac{ki}{n}$$

where

v = average interstitial velocity

k = hydraulic conductivity

n = porosity

i = hydraulic gradient = $\Delta h/\Delta l$

Δh = change in head between two points of concern in the aquifer

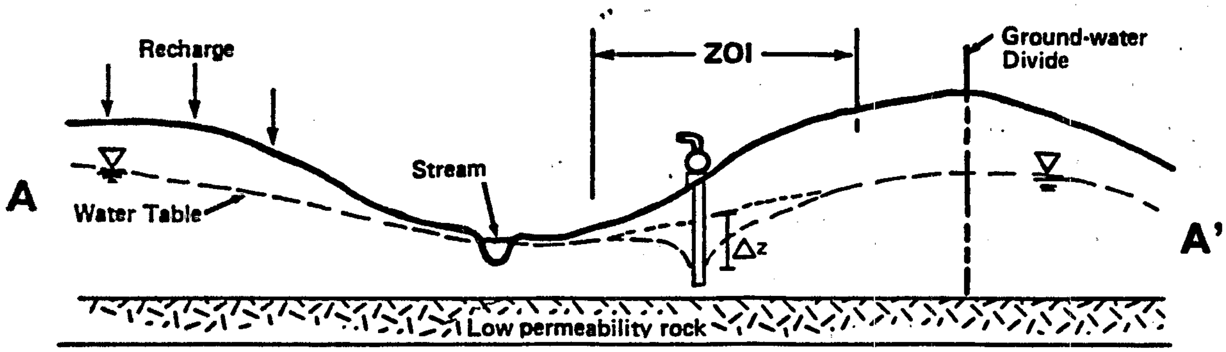
Δl = distance between these points.

2.1.2 Pumping of Ground Water

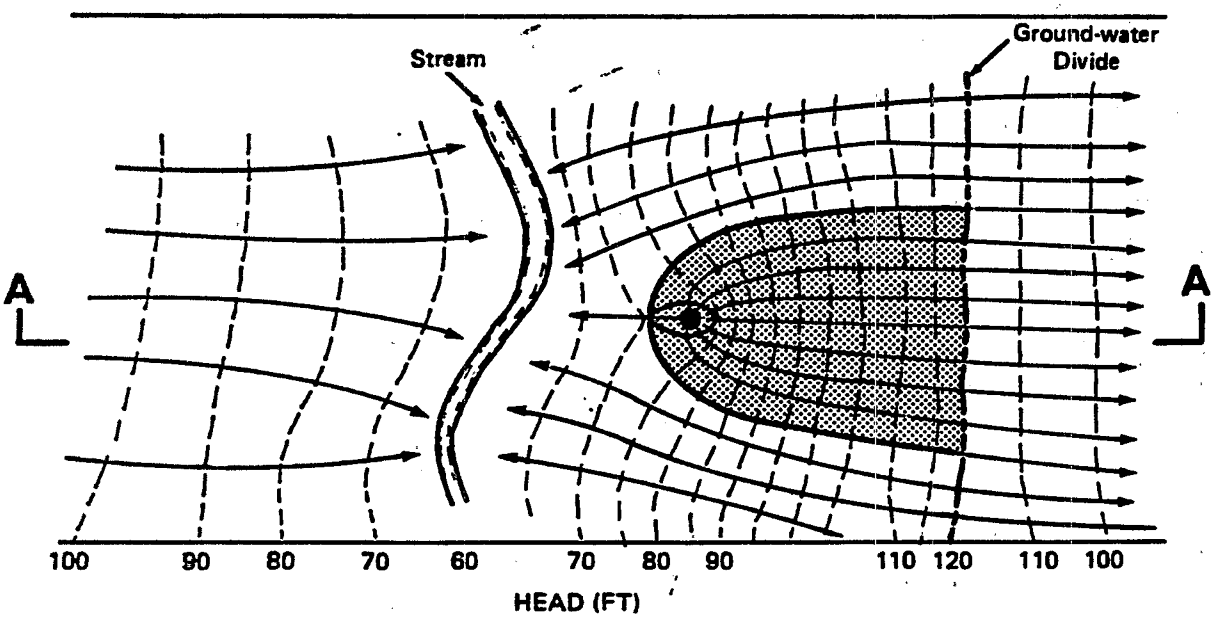
The use of ground water as a source of drinking water normally requires the installation and operation of a well or well field. Ground-water pumpage alters the natural state of equilibrium in an aquifer. The withdrawal of water by a well causes a lowering (drawdown) of water levels in an area around the well. From a spatial perspective, this is referred to as the "area of influence" of a well, or its "zone of influence" (ZOI). In cross-section, this is commonly referred to as the "cone of depression." Within the ZOI, flow velocities increase toward the well, due to increased hydraulic gradients.

Figure 2-2 illustrates the effects of a pumping well on the ground-water flow system of the same hypothetical stream valley introduced earlier. The ZOI of the well is shown in Figure 2-2a. Figure 2-2b shows that the equipotential and flow lines for the "natural" (nonpumping) conditions have been distorted, and are directed toward the well. This distortion causes an area of ground-water recharge to the well. The pumping does not affect the flow lines outside of that area. It should also be noted that the pumping of the well causes some of the ground water that previously flowed directly to the stream to reverse its path and flow back toward the well. The entire area recharging or contributing water to the well or well field is defined in this document as the zone of contribution (ZOC). Other authors use similar terminology (e.g., Morrissey, 1987), or refer to this as the "capture zone" (Keely and Tsang, 1983). The areal extent of the ZOC can increase with time as the well continues to pump. These transient zones are referred to as "time-related capture zones."

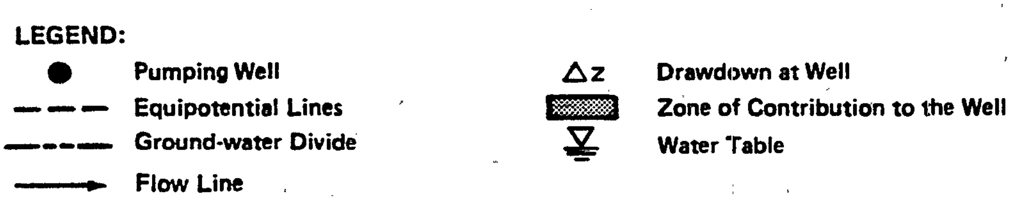
Figure 2-2
Ground-water Flow System (Stream Valley) Affected by a Pumping Well



a) CROSS SECTION



b) PLAN VIEW



SOURCE: Modified from Driscoll, 1986

The two zones described above (ZOC, ZOI) are referred to extensively throughout this document because of their significance to WHPA development. The ZOC is of greater importance because contaminants introduced within this zone could reach a well. The contaminants would travel very rapidly toward the well once they enter the portion of a ZOC where ground-water levels are significantly lowered by pumping.

The historic confusion over these two concepts, and perhaps the overemphasis in some ground-water protection efforts on the ZOI or cone of depression, is stated succinctly by Morrissey (1987):

> The fallacious idea that contributing area and area of influence are identical persists....(This confusion may have contributed to the use of circular areas around wells as buffer zones for ground-water-quality protection.) Actually these areas can be the same only in the hypothetical circumstances where the pre-pumping water table is perfectly flat and all aquifer properties are uniform within the area of influence. When the pre-pumping water table has a gradient, as it does under most natural conditions, the contributing area to a well will be distorted to extend to a greater distance on the upgradient side and to a lesser distance on the downgradient side.

and

> Recharge that enters the aquifer through the area of influence of a well will not necessarily travel to the well, and recharge that enters the aquifer outside the area of influence may travel to the well.

Generally, the most significant process controlling the movement of contaminants within the ZOC is called "advection," in which contaminants are carried toward a well by the bulk motion of the flowing ground water. Chemical, biological, and physical processes other than advection may affect the fate of contaminants in ground water. Retardation and dispersion are two processes that respectively slow and accelerate the movement of a contaminant toward a pumping well. Relevant properties of contaminants that could affect their movement toward a well or spring are briefly discussed in Section 2.3.

Finally, it should be noted that while many surface bodies serve as boundaries to flow (the situation depicted in Figures 2-1 and 2-2), many do not. Pumping can induce flow not only from the surface water bodies themselves, but (due to underflow) also from areas on the opposite side of the surface water body from the well. In such situations, contaminants within surface waters or from other aquifer segments can be induced to move toward the pumping well. Analyses of the extent and occurrence of this phenomenon, and the impacts on WHPA delineation, will be an important factor in some hydrogeologic settings and in some State programs.

2.2 OTHER AQUIFER CONSIDERATIONS

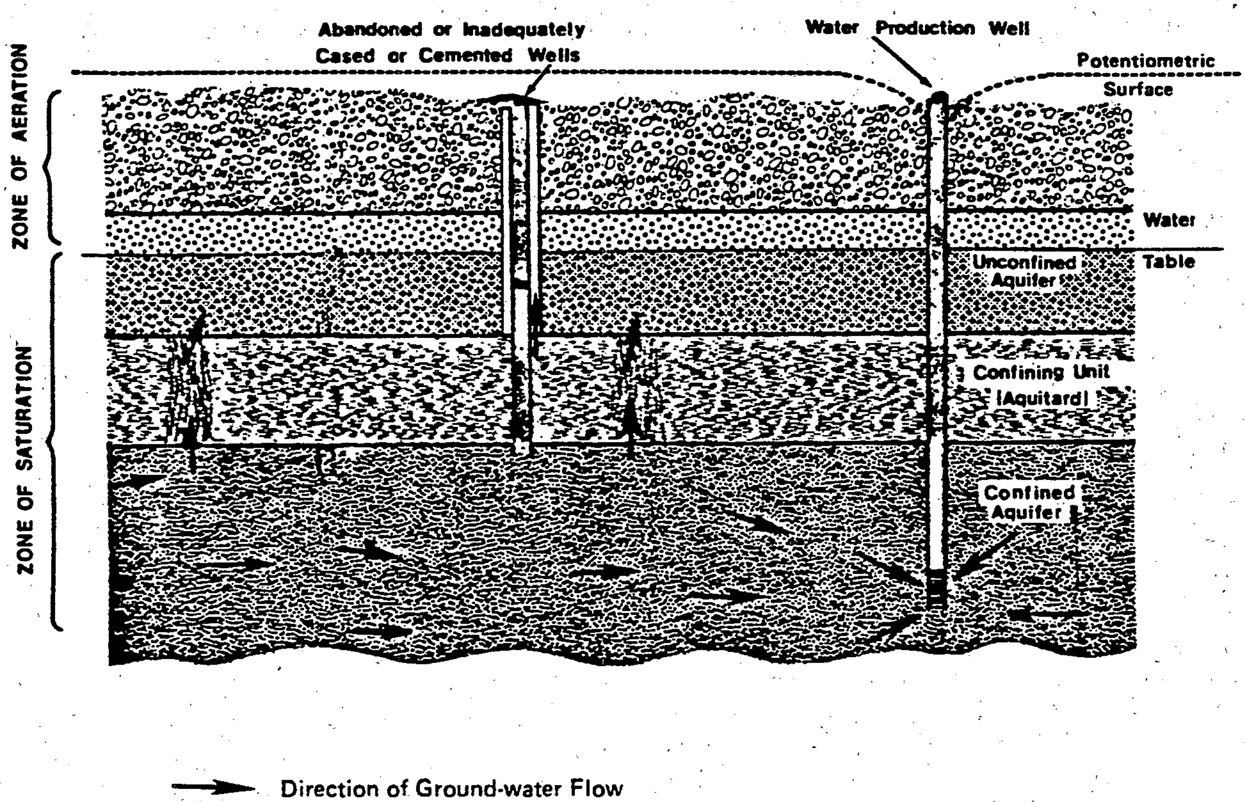
Aquifers in porous, granular materials are commonly divided into two types, unconfined and confined, on the basis of stratigraphic setting and hydraulic pressure (head) relationships. Unconfined aquifers have an upper water surface (water table) that rises and falls freely in response to the volume of water in storage in the aquifer. The water table is a free surface open to, and in pressure equilibrium with, the atmosphere. The upper water surfaces of such aquifers may lie a few feet or tens of feet beneath the surface in humid regions. In arid or semi-arid alluvial settings, the water table may be several hundred feet below the surface. The depth to the water table and the nature of the unsaturated zone above an unconfined aquifer can be significant in controlling how rapidly contaminants are able to reach the aquifer. Much is known about unconfined, granular aquifers. These aquifers have received the bulk of attention in the scientific literature Other aquifer types such as confined, karst, and fractured rock settings are less well understood. The remainder of this section is therefore directed to a review of hydrogeologic factors of these settings relevant to WHP.

2.2.1 Confined Aquifers

Confined aquifers occur beneath a lower permeability "confining unit" of rock or sediment. Pressure in the aquifer is greater than atmospheric, so that water will rise above the base of the confining unit in a well penetrating that confining horizon (Figures 2-3 and 2-4). This situation is also commonly known as "artesian." The relative head relationships across the confining unit are key factors in understanding the required extent of a WHPA, as well as the need for particular management strategies. If the head (as expressed by the potentiometric surface) of a confined aquifer is above that of the overlying unconfined aquifer (i.e., the water table), contaminants would likely remain in the unconfined aquifer, due to the tendency for upward flow across the confining unit (as shown in Figure 2-3). Conversely, should the potentiometric surface in the confined aquifer be lower than the water table, downward leakage of water and contaminants is possible (Figure 2-4).

Apart from these hydraulic head relationships, the low permeabilities of confining units overlying confined aquifers can reduce both the travel times to and contaminant concentrations in the aquifer, so that the contaminant may pose a reduced threat to the

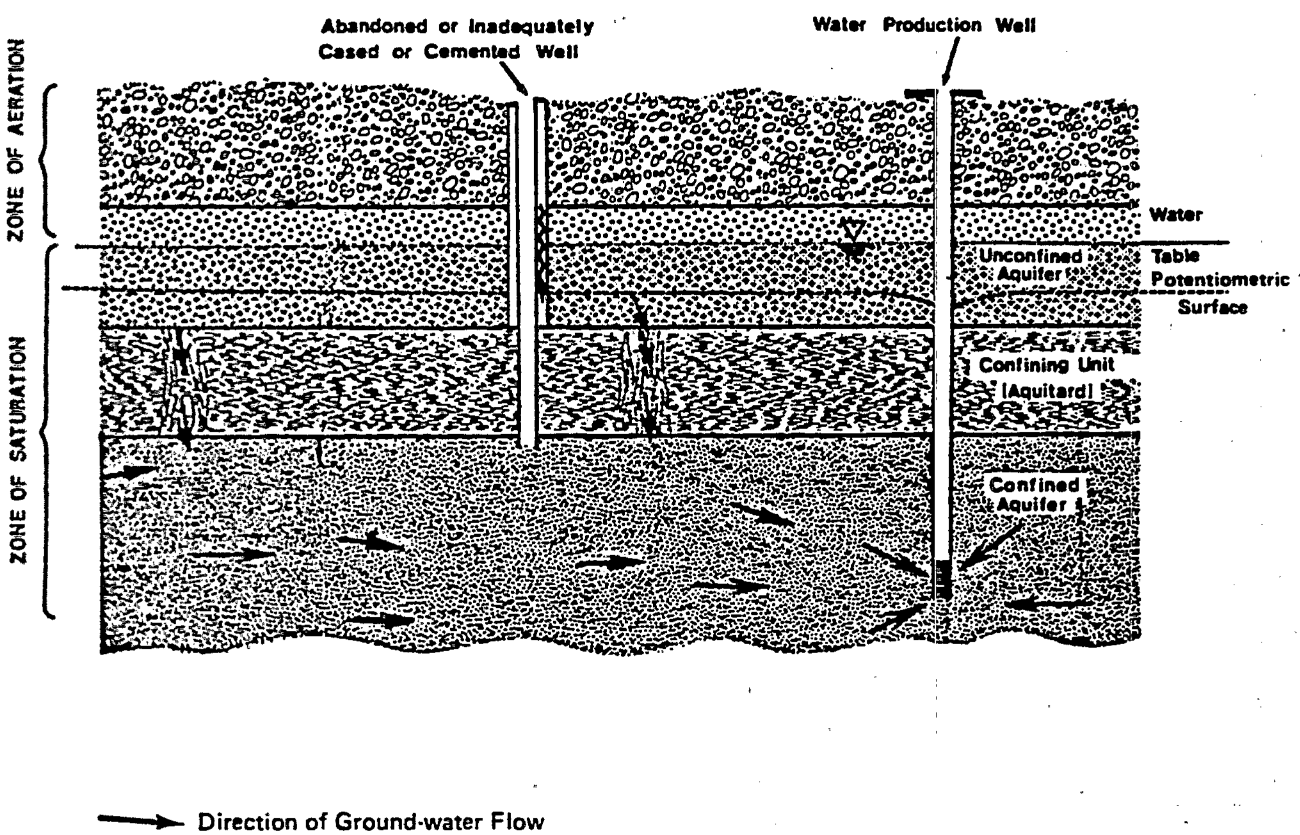
Figure 2-3
Confined Aquifer with Upward Leakage



SOURCE: Everett. 1987

NOT TO SCALE

Figure 2-4
Confined Aquifer with Downward Leakage



SOURCE: Everett, 1987

NOT TO SCALE

aquifer. Major areas of concern, however, lie with natural or manmade breaches in confinement, such as incised channels in confining beds or abandoned wells. Relative head relationships in these situations may permit inward flow or leakage of contaminants from overlying units.

As a result of pumping over a period of time, confined aquifers may have their hydraulic pressure lowered until the surface of water adjacent to the well bore is no longer in contact with the base of the confining unit. Thus, the water surface is in a water table condition in the cone of depression, although it is still "stratigraphically" confined.

Most confined aquifers are actually semiconfined, being leaky to some extent. Leakage is not in itself evidence of contamination; many confined aquifers derive a significant amount of recharge from this source. Rather, leakage indicates an influent condition that could introduce contaminants into an aquifer where they are able to reach the leakage pathway.

As relative heads change to permit inflow to the confined aquifer, it can be presumed that the relative risk of contamination to the aquifer will increase. The potential for introduction of contamination is roughly proportional to the difference in heads and hydraulic conductivity of the confining unit. The area most subject to rapid contaminant inflow would thus be in the area of lowest relative aquifer head; that is, low elevation in the aquifer's potentiometric surface. Analysis of hydraulic head differentials and identification of potential pathways should provide a basis for evaluating the risk to wells or well fields in confined aquifers.

Shallow, Poorly-Confined Conditions. Fractures in fine-grained confining sediments under near-surface conditions can provide significant natural pathways for contaminant migration. Although fractures have been observed to penetrate to depths of about 60 feet in glacial till, they are usually restricted to much shallower depths under shallow water table conditions (Cartwright, personal communication, 1987). The permeability resulting from near-surface fracturing is significantly greater than similar fracturing at depth. This is because the effect of increasing horizontal in-situ stress is to decrease both the aperture width and spacing frequency of fractures. Permeability of unconsolidated sediments (due to primary porosity) is also greatest near the surface, decreasing with depth.

Conditions of increased fracture permeability in fine-grained sediments and higher near-surface primary-porosity permeability combine to cause the zone of greatest risk of contaminant transport into a confined or semiconfined aquifer to be near the surface. As a result, it can be considered that shallow, poorly-confined aquifers (100 feet or less below the surface) have approximately the same risk of contamination as do unconfined aquifers. If data exist to indicate that such aquifers are as effectively confined from surface and shallow subsurface contaminants as are deeper confined aquifers, a less stringent approach may be considered.

Intermediate Confined Conditions. Between depths of 100 and 300 feet, confinement characteristics are difficult to predict because they are very dependent on local circumstances. In this intermediate zone, some confined aquifers are very leaky. Fluids may move downward with ease through poorly consolidated sediments, fracture-prone thin siltstones, carbonate rocks, and sandstones of low permeability. In other settings, aquifers of this depth can be well confined by fine-grained sediments or consolidated rocks.

The intermediate zone lies below depths where good soils and engineering data on permeability are frequently available (usually only for the range from the surface to 20 feet). It is also beyond the depth range for which most laboratory and field test data are developed. Intermediate-depth confined aquifers are so subject to the specific characteristics of individual sites that generalizations relative to WHPA delineation are difficult to support. Approaches should therefore be developed on a class-by-class (where regional similarities exist) or well-by-well basis.

Deep Confined Conditions. Aquifers that are deeper than 300 feet below the surface are at the upper (shallow) end of the data sets showing field or laboratory measurements of fracture hydraulic conductivity and permeability, or else are sufficiently close to such data that reasonable extrapolations of properties can be made. In addition, the extent of contaminant attenuation that can occur during vertical transport to the deep units adds to the margin of safety. Except in such settings as the coastal plains and deep alluvial basins, confined porous granular aquifers are frequently consolidated below 300 feet. This means that permeabilities are greatly reduced in comparison with their unconsolidated analogues. In such circumstances, the cone of depression can be a significant indicator of relative head and potentiometric surface relationships between a confined aquifer, its confining units, and adjacent aquifers.

Where leakage occurs through adjacent strata, recharge is generally greater in the deepest parts of depression cones, decreasing with distance from a pumping center. The recharge rate increases as the potentiometric surface declines and the vertical head loss increases (Walton, 1970). Neuman and Witherspoon (1969) and subsequent studies have discussed some of the complexities of assumptions and their consequences in the analysis of leakage. Nonetheless, Walton's generalizations appear valid.

The volumetric extent of aquifer leakage occurs over a wide range. Some poorly confined aquifers can produce a high ratio of water from leakage relative to that from storage. More tightly confined aquifers will have a small ratio of leakage to storage water. As was indicated previously, leakage only indicates the possibility of contamination, should contaminants enter a leakage path into a confined aquifer. In cases where leakage is from water stored in the confining unit, it may be that no discrete leakage path exists across the confining unit to an overlying aquifer.

Deep confined aquifers should be evaluated on the basis of various factors. The effectiveness of natural confinement is a major consideration, taking into account natural breaches (such as fractured or eroded confining units) and changes in hydraulic conductivity from changes in facies of confining horizons. Manmade breaches, such as active and abandoned well bores, are quite significant to the possibility of contamination threats. Relative differences in head between the aquifer, confining units, and adjacent aquifers are also important.

2.2.2 Karst and Fractured Bedrock Aquifers

Although there is a broad range in flow velocities among granular, porous aquifers, it is apparent that flow conditions in other types of aquifers need to be considered. Both karst and fractured bedrock aquifers can be in either unconfined or confined settings. In unconfined and poorly confined conditions, these aquifers can have very high flow (and contaminant transport) rates under rapid recharge conditions such as storm events. Transport times across entire karst or fractured bedrock flow systems may be as short as hours to weeks, much briefer than in porous, granular aquifers. For this reason, these susceptible aquifers should be evaluated differently from the more common porous, granular aquifers.

Solution enhancement of bedding plant joints and fractures in karst aquifers creates large pathways. As a result, flow velocities in karst aquifers having conduit flow can range over several orders of magnitude between high-flow and normal-flow conditions.

Because karst aquifers can include both conduit and diffuse flow paths, different flow mechanisms can supply water to well and spring discharges concurrently. Diffuse flow systems can frequently be modeled and evaluated using the methods for porous, granular aquifers, but conduit flow situations are not effectively analyzed in the same manner.

Karst aquifers can be divided into diffuse flow, mixed diffuse and conduit flow, and conduit flow. Under conduit flow conditions, contaminants can be transported quite rapidly in the system from their point of introduction to the point of delivery, with only minimal dilution or dispersion. Similarly, conduit karst can often undergo rapid flushing of contaminants from the system. As a result of different conducting channels within conduit flow systems, contaminants in one set of channels may not interconnect with adjacent channels. Thus, the pattern of water quality during a contamination event can differ considerably from that which would occur in porous, granular aquifers.

Fractured bedrock aquifers share many characteristics with conduit karst aquifers. However, they often cannot match the higher flow velocities in karst, because fracture apertures have not been enlarged to the same extent by dissolution. Fractured bedrock aquifers generally have relatively little storage capacity in the pore space of the aquifer compared to that in porous, granular aquifers. If they are capable of significant water supply, this is usually the result of interconnections with alluvial aquifers, saturated saprolites, or surface water bodies. They are characterized by rapid and large rises in the water table during recharge/maximum flow events, and can be influenced by recharge from a large portion of the effective drainage basin.

As discussed in Chapters 3 and 4, unconfined and poorly confined, conduit flow, karst, and bedrock aquifers that are characterized by high-flow events will likely be delineated initially by mapping the general physical boundaries of their drainage basins. Water table elevations under normal and high-flow conditions will also provide relevant data. Subsequently, more precise delineation of flow can be conducted to determine those portions of the drainage basin that actually contribute to a well or spring. This effort can be based upon use of dye or other tracing techniques.

Finally, the approach to WHPA delineation in more effectively confined karst and fractured bedrock aquifers that are isolated from both surface water and shallow, rapid-flow-response aquifers can be the same as that for other deep, confined aquifers.

2.3 CONTAMINANT PROPERTIES

Subsection 1428(a) of the SDWA requires States to adopt programs "to protect wellhead areas...from contaminants which may have any adverse affects on the health of persons." Subsection 1428(a)(3) further states that these programs must as "a minimum...identify within each wellhead protection area all potential anthropogenic sources of contaminants which may have any adverse effect on the health of persons." Based on the current knowledge of contaminant characteristics, ground-water management strategies, and other WHP factors, there is no one operational approach that will be suitable for meeting this general goal. Each State will likely choose its own approach and rationale. It is clear, however, that some knowledge of contaminant properties is essential for understanding the adequacy of WHP delineation.

Many different types of contaminants exist; those of most concern can generally be classified as inorganic and organic chemical compounds and elements, bacteria, and viruses. It is important to identify what is known about specific contaminant types in assessing their significance in WHPA delineation. The remainder of this chapter reviews some of the major properties that affect the persistence and mobility of contaminants in these groups. These properties form the basis for understanding WHPA criteria, the subject of Chapter 3.

2.3.1 Inorganic Chemicals

Some of the most common and mobile contaminants result from the release of inorganic chemicals into ground water. Such constituents as nitrate, ammonia, sodium, and chloride often cause persistent problems due to their high solubility in ground water. For example, nitrate contamination from sewage and agricultural practices occurs over large areas in many shallow aquifers. Salt water problems from highway deicing storage depots, seawater infiltration, and brine upwelling have degraded ground-water supply sources that have been stressed due to overpumping.

The primary mode of inorganic contaminant movement is through advection. Retardation processes occur through denitrification, adsorption, bacterial decomposition, precipitation, and chelation--all of which are considerably less effective under saturated conditions. The most effective mechanisms of concentration reduction in ground water are dispersion and dilution.

A relative ranking of the mobility of common inorganic chemical pollutants that are characteristic of municipal waste leachates shows very significant attentuation of heavy metals moving through clay, whereas there is only slight retardation of water-soluble organic constituents exerting a chemical oxygen demand (Griffin and Shimp, 1978; Griffin, et al., 1976). The comparative effectiveness of different clay minerals and of iron and aluminum oxyhydroxides in removing heavy metals has been demonstrated (Griffin and Shimp, 1976; Kinninburgh, et al., 1976). Oxidizing conditions in soils and water lead to precipitation of iron, manganese, and aluminum oxyhydroxides, scavenging other metals as well. On the other hand, oxidizing conditions in water can maintain dissolved nitrate concentrations that can be readily reduced under biological or chemical reduction conditions.

Although certain metals may persist for long periods in ground water, their mobility is generally lower than other more "conservative" inorganics such as nitrates and chlorides. This is due to the relative low solubilities of many metals under most ground-water conditions and to their tendency to be adsorbed on clay minerals, on hydrous oxides of iron and manganese, and on organic matter. Isomorphous substitution or coprecipitation with minerals or amorphous solids can also be important (Freeze and Cherry, 1979).

The solubility of metals is generally controlled by the most abundant anions in natural ground water. These are hydroxyl, bicarbonate, sulfate, chloride, nitrate, and (in reducing environments) sulfide ions. The mobility of metals depends on the solubilities of their hydroxides, carbonates, sulfates, chlorides, sulfides, and organic complexes (Matthess, et al., 1985). The movement of metals, as with other inorganic species, is primarily by advection.

2.3.2 Organic Chemicals

Although many organic chemicals occur naturally in the subsurface environment, the effects of certain synthetic organic chemicals are becoming of concern in most State ground-water protection efforts. These chemicals include, among others, solvents, pesticides, and synthetic hydrocarbons. Organic chemicals may be removed from ground water by a variety of means. Chemical reactions, microbial activity, and cometabolism either reduce the concentrations of organics or metabolize and destroy the chemicals by transformation or consumption. The rate of degradation is influenced by such factors as the volume of contaminant, its miscibility and solubility in water, temperature, pH, oxygen content, the availability of certain organic and inorganic materials, and the character of the substrate (Helling, 1971; Iwata, et al., 1973; Griffin, et al., 1979).

Decomposition is especially enhanced by micro-organisms, which are most active in soils and in aerobic, shallow, unconfined aquifers. It is uncertain whether this is the result of transformation to secondary organic compounds or complete mineralization. However, decomposition rates are much slower in ground water than in the soil. Consequently, organic chemicals can be quite persistent after ground-water contamination has occurred.

Table 2-1 lists the persistence of several organic materials in ground water and soils. Some pesticides may contaminate ground water due to their higher leaching potentials. It can be seen from this table that certain organic contaminants are very persistent, especially in ground water. For example, DBCP has a half-life of about 10 weeks in the soil, in contrast with up to 140 years in ground water.

A growing concern lies with a phenomenon called "facilitated transport" (Tomson, et al., 1987). Contaminants that have been considered relatively immobile, such as dioxin and metals, have been discovered at great distances from their sources. It appears that organic solvents can greatly affect the mobility of these contaminants. Recent information also indicates that colloids and macromolecules appear to facilitate movement of contaminants, enabling them to disperse faster than the average ground-water flow rate. The full impacts of this phenomenon on the transport of metals and organic chemicals are not yet known. Implications on selecting WHPA criteria thresholds are discussed in Chapter 3.

2.3.3 Bacteria and Viruses

The survival of pathogenic micro-organisms (e.g., parasitic and enterotoxin-producing bacteria) in the subsurface environment has been a key component of public health concerns for drinking water protection for many decades. Allochthonic bacteria (those artificially introduced) are usually eliminated in the subsurface environment, generally faster than organic chemicals. In oxygen-rich environments, bacteria can survive for fairly long periods (greater than 6 months) in the deeper parts of the unsaturated zone and in ground water.

The elimination of pathogens results from the combined effects of the physical (including temperature), biological, and chemical conditions that exist at a site. The availability of nutrients and biological factors is most important for the survival of pathogenic bacteria. Elimination is faster at high temperatures (37° C), at pH values of about 7, at low oxygen concentrations, and at high levels of dissolved organic carbon.

TABLE 2-1

Persistence of Organic Substances in Ground Water and Soils

Organic Chemical	Estimated Half-Life (years)	
	In Ground Water	In Soils
Hydrocarbons		
Benzene		1
Toluene		0.3
Xylene		0.3
Ethylbenzene		0.3
C_3 Benzene		0.6
Napthalene		0.6
Halogenated Hydrocarbons		
Dichloromethane		10
Trichloroethane		2
1,1,1-Trichloroethane		1
Dichlorobenzene		1
Pesticides* (solubility in water)		
Chlordane		2 to 4
DDT		3 to 10
Dieldrin		1 to 7
Heptachlor		7 to 12
Toxaphene		10
DDVP		0.047 (17 days)
Methyl demeton S		0.071 (26 days)
Thimet		0.005 (2 days)
Pesticides** (high solubility in water)		
EDB	5.8	0.04-0.35 (2-18 weeks)
DBCP	28.5 to 140	0.2 (10 weeks)
Aldicarb	0.2 to 12.5	0.08-0.15 (4-8 weeks)
Atrazine	0.2 to 2	0.08-1.1 (4-57 weeks)
Carbofuran	0 to 1	0.02-0.7 (1-37 weeks)

Source: *Matthess, et al., 1985
**Cohen, et al., 1984

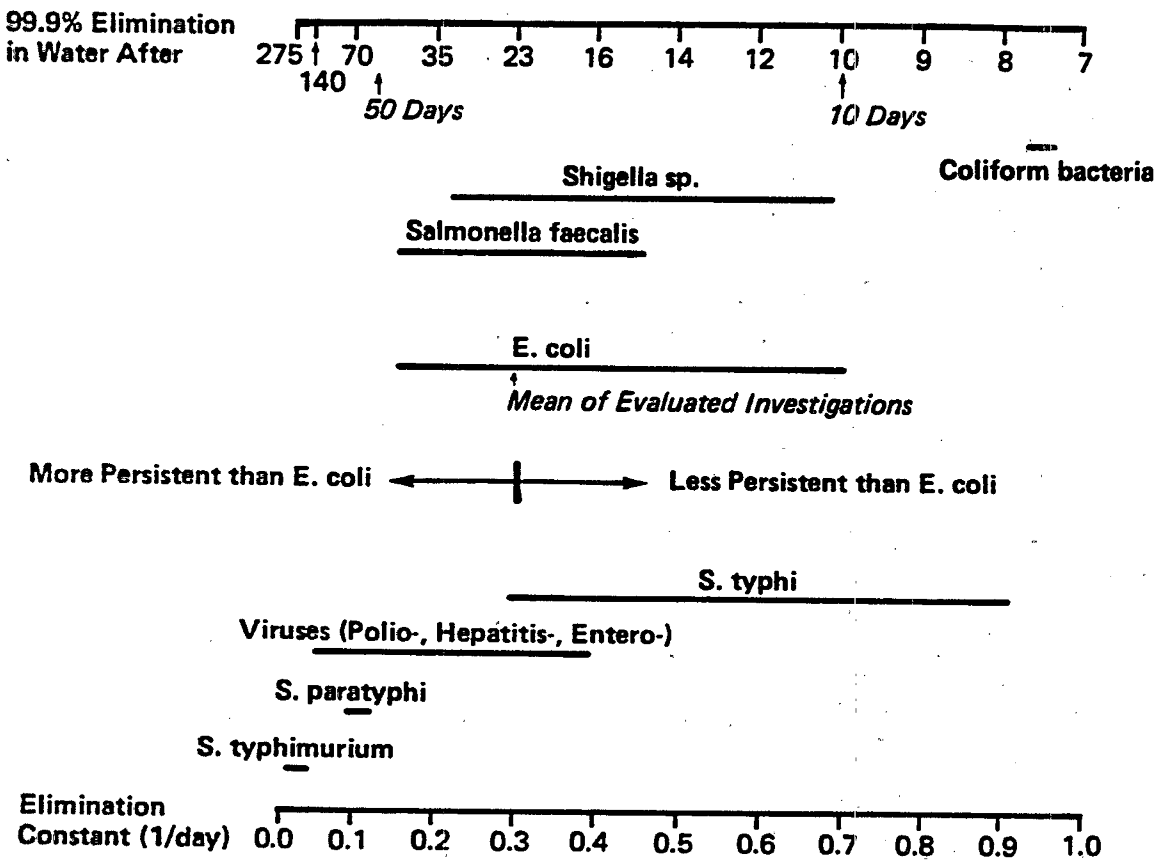
Under these conditions, naturally occurring bacteria are activated, which act antagonistically towards pathogenic microorganisms in the waste materials.

Elimination is specific for different microbial species (Figure 2-5). For example, Coliform bacteria will reach a 99.9 percent elimination in less than 8 days, while it takes 50 days for E. Coli to attain the same level of elimination. Under oligotrophic conditions and at temperatures below 15° C, Salmonella typhi can survive more than 100 days, Salmonella typhimurium approximately 230 days, and Yersinia sp. approximately 200 days (Matthess and Pekdeger, 1981). Several factors control the survival and migration of viruses once they have been introduced into the subsurface environment. In general, the climate, clay content and moisture-holding capacity, and virus type are the major elements in determining virus fate. Viruses can migrate considerable distances underground; virus penetrations to depths as great as 67 meters and horizontal migrations as far as 408 meters have been reported (Keswick and Gerba, 1980).

Considerable emphasis has been placed on examining the persistence of viruses in ground water. A recent study determined that temperature was the only variable significantly correlated with the extended survival of three viruses examined. In addition, it was observed that the viruses persisted for longer periods in well water samples than in surface waters incubated at similar temperatures. At the lower temperatures characteristic of ground water in most areas of the United States, Poliovirus 1 and Enchovirus 1 persisted for very long periods, up to 28.8 days, before a significant reduction was achieved (Yates, et al., 1985). Figure 2-5 indicates that 0.1 percent of Poliovirus, Hepatitisvirus, or Enterovirus can survive after a 140-day period in ground water, which is considerably longer than the survival of E. Coli bacteria. Under favorable oligotrophic conditions and at temperatures less than 15° C, Poliovirus can survive for over 250 days (Matthess and Pekdeger, 1981).

From these and similar findings based on field studies, it has been recommended in Europe that delay times of at least 50 to 60 days, and where possible as much as 1 year, should be provided to protect wellheads from virus and pathogenic bacteria contamination. In addition, due to scale dependency factors and regardless of delay times, a minimum 100-meter (325-foot) distance is required (Matthess, personal communication, 1987). These conclusions have been derived from an extensive, multi-year research program (Matthess, et al., 1985).

Figure 2-5
Elimination Constant and 99.9% Elimination of Some Relevant Bacteria and Viruses in Ground Water



SOURCE: Matthess, et al., 1985

2.4 DELINEATION ZONE PROPERTIES AND TERMINOLOGY

The concepts of natural ground-water flow, the influence of pumping, the rates of travel, and contaminant transport are introduced in the earlier sections of the chapter. At present, these concepts form the elementary principles used in most WHP programs. As will be discussed in Chapter 3, existing WHP programs are generally aimed at one of the following overall protection goals:

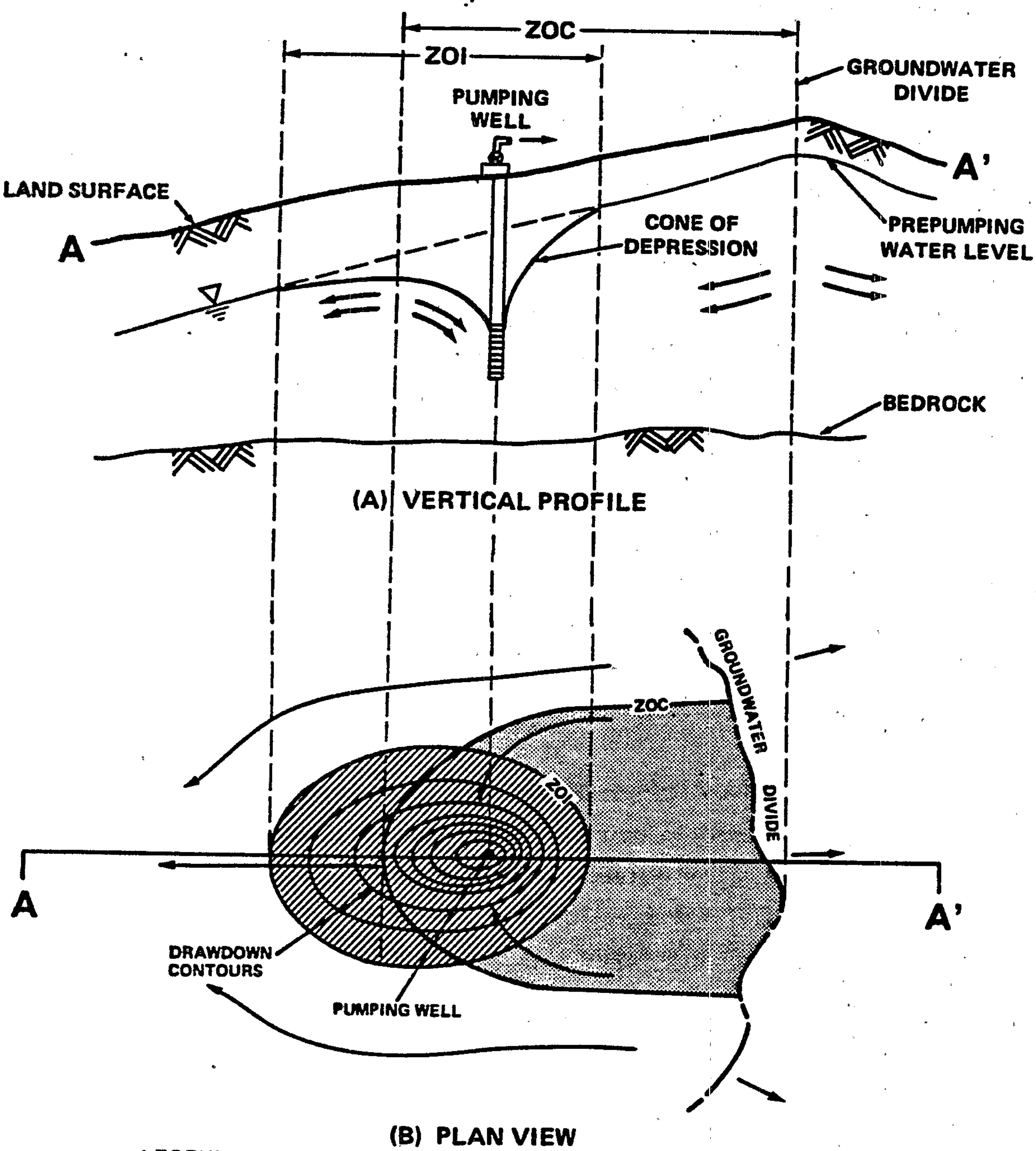
- Provide a remedial action zone to protect wells from unexpected contaminant releases.
- Provide an attenuation zone to bring concentrations of specific contaminants to desired levels at the time they reach the wellhead.
- Provide a well-field management zone in all or part of a well's present or future recharge area.

Several approaches have been utilized to accomplish the goals listed above. The approaches require operational procedures for delineating WHPA's for a variety of settings. Five hypothetical situations in different hydrogeologic settings are described below to illustrate the applications of these generalized approaches. The application of each approach is based on specific criteria (such as time of travel or drawdown) that form the basis for several delineation methods. The criteria and methods used in WHPA delineation are discussed extensively in the chapters following. The purpose of this discussion, however, is to depict the differences in criteria and method application based on a range of aquifer types.

The first example is depicted in Figure 2-6. A pumping well is shown to have created a cone of depression within an unconfined ground-water flow system. The aquifer consists of an unconsolidated porous media overlying bedrock. The ZOI of the well is the area overlying the cone of depression. The ZOC is the entire flow system that supplies water to the well, including in this case a large portion of the ZOI. The full extent of the ZOC would represent a more accurate appraisal of the area in which ground water actually flows to the pumping well.

The second illustration (Figure 2-7) depicts (by shading) zones of hypothetical transport of a contaminant in the same aquifer. The time for a contaminant to travel from a point to a well is identified by contours of equal travel time (isochrones). The zones within the isochrones are referred to as "zones of transport" (ZOT's). Large ZOT's

Figure 2-6
Terminology for Wellhead Protection Area Delineation (Hypothetical Pumping Well in Porous Media)

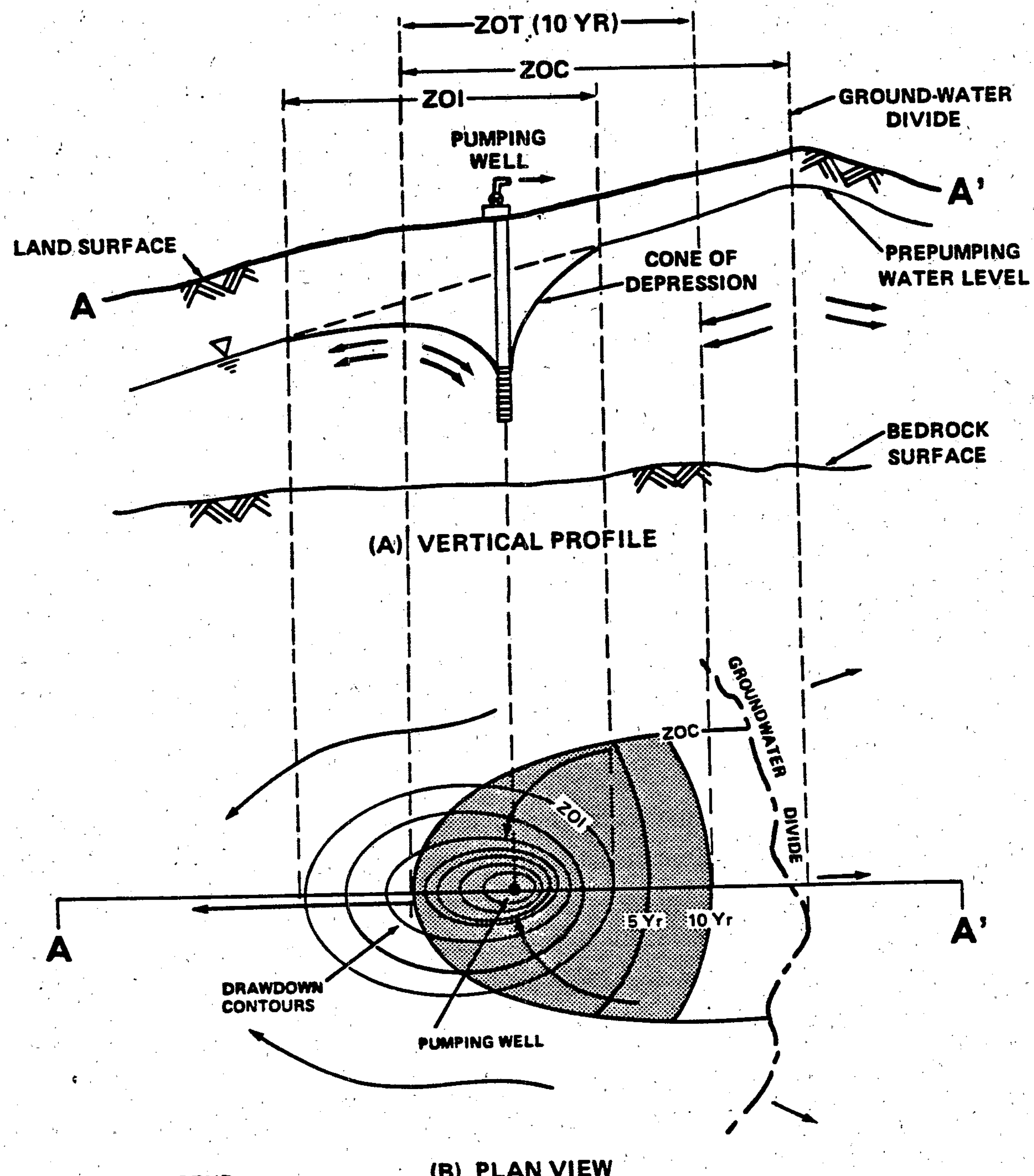


LEGEND:

- ▽ Water table
- ——▶ Ground-water Flow Direction
- ● Pumping Well
- ZOI Zone of Influence
- ZOC Zone of Contribution

NOT TO SCALE

Figure 2-7
Terminology for Wellhead Protection Area Delineation (Hypothetical Contaminant Transport in Porous Media)



LEGEND:

- Water Table
- 10 Year Zone of Transport
- Direction of Ground-water Flow
- ZOC Zone of Contribution
- ZOI Zone of Influence
- ZOT Zone of Transport

NOT TO SCALE

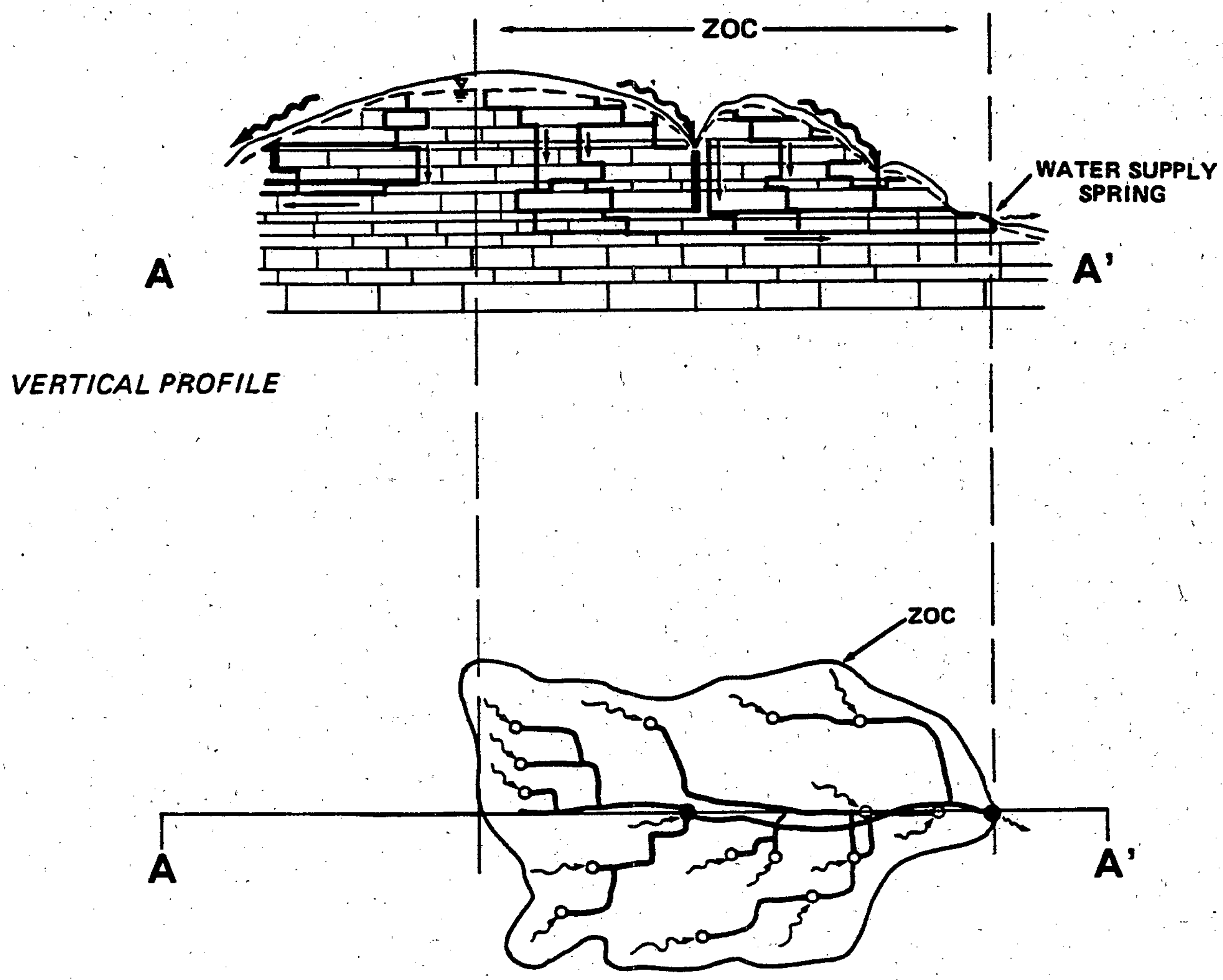
are shown for areas near the ground-water divide far from the pumping well. The larger the ZOT (i.e., the larger the TOT threshold), the more protective the WHPA. Very small ZOT's are shown within the area of influence of the well, where contaminant travel times are significantly accelerated due to the high hydraulic gradients and flow velocities in this area. The ZOT is part of the ZOC, however.

The third situation (Figure 2-8) depicts a ground-water flow system in a mature karst setting. The discharge is to a spring used as a public water supply source. The flow is generally confined to a complex network of solution channel and cavernous conduits that is extremely difficult to infer from the surface. An approach in such a situation might be to delineate WHPA's based on the boundaries of the ZOC being inferred as the divides or drainage boundaries of the setting.

The fourth example (Figure 2-9) presents a pumping well in a fractured bedrock aquifer that has been placed at the intersection of two fractures. This well location takes advantage of the higher permeability and storage provided by the fracture zone. Flow to the well is controlled by the distribution and degree of interconnection that exists between fractures and by the variations in aquifer recharge due to rainfall. It is extremely difficult to define the actual recharge area of a well in a fracture setting. An assumption that the topographic divides or drainage boundaries of the setting represent the ZOC may be the basis for WHPA delineation here.

The final example (Figure 2-10) illustrates a pumping well in a confined aquifer in porous media. In this case, the prepumping potentiometric surface of the confined aquifer has been lowered below the water table of the overlying unconfined aquifer. The confining layer may provide some protection to the water source. However, the dominant vertical direction of potential contaminant flow in the area where the potentiometric surface is lower than the unconfined water table suggests that this should be examined as an area of concern for WHPA delineation. This would focus the search for abandoned wells, fractures, and other features that could penetrate the confining layer. Another approach might focus on a portion of the contributing area, based upon some TOT threshold within the aquifer.

Figure 2-8
Terminology for Wellhead Protection Area Delineation (Hypothetical Ground-water Basin in Mature Karst)



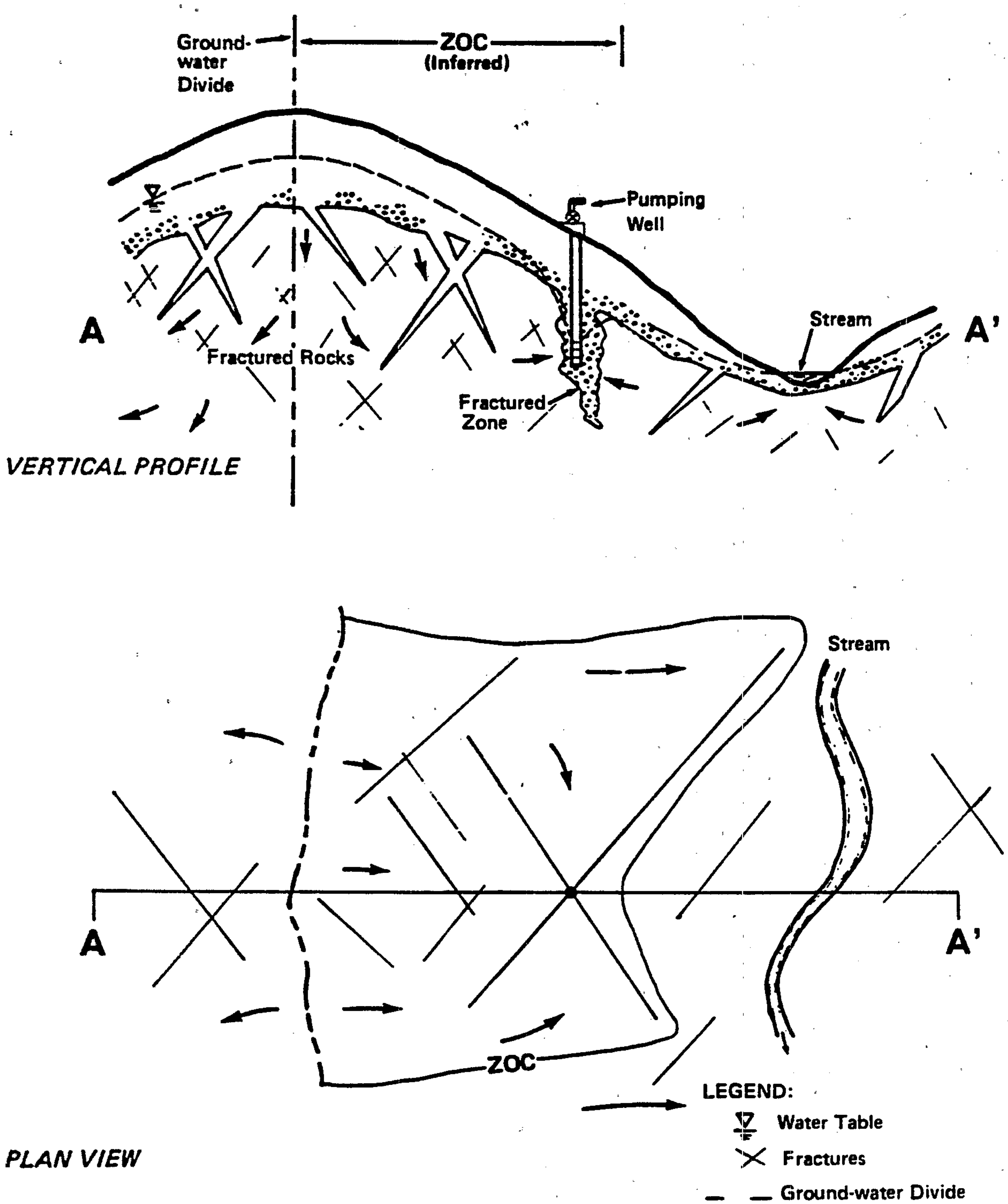
LEGEND:
- Sinkhole
- Water Supply Spring
- Surface Stream
- Conduit System
- Water Table
- Limestone

NOTE: The "ZOC" shown was delineated with purpose of including all principal areas contributing to the cave based on inferred surface and subsurface drainage areas.

SOURCE: Modified from Quinlan and Ewers, 1985

NOT TO SCALE

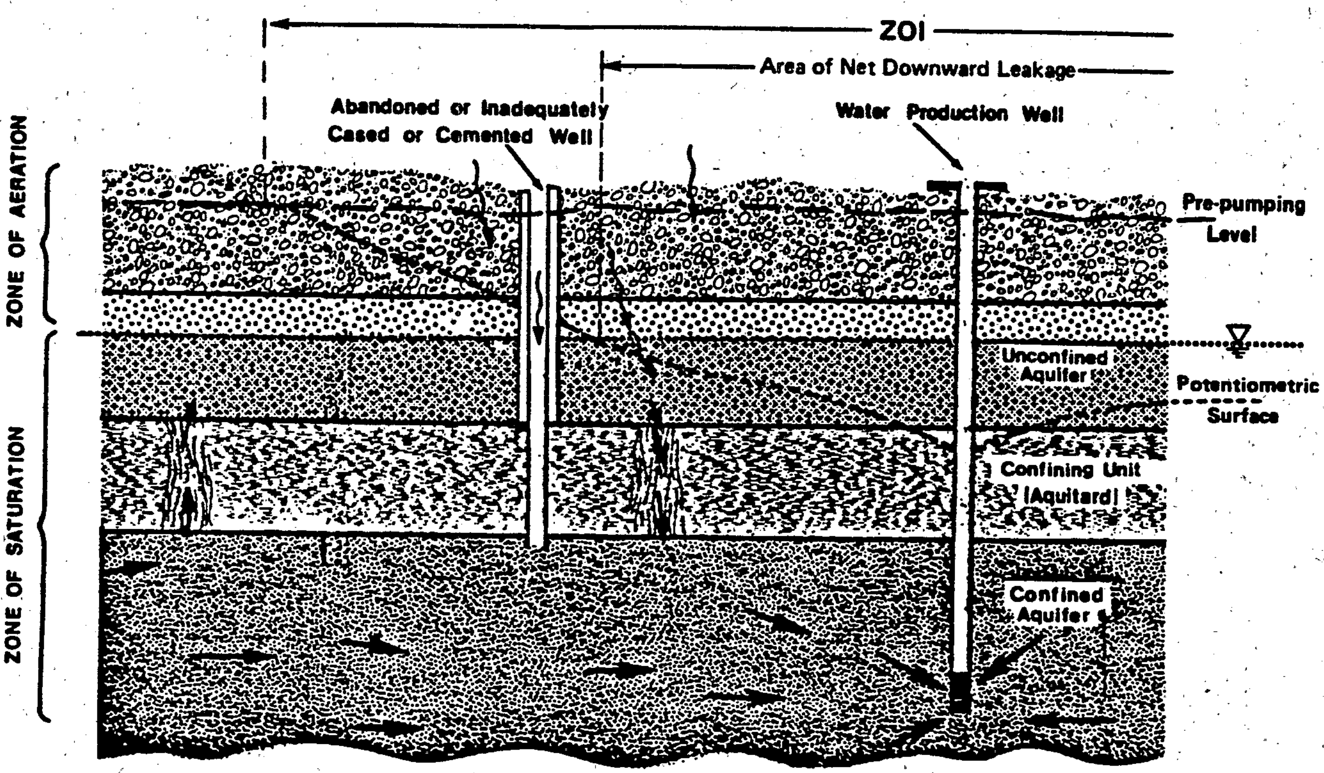
Figure 2-9
Terminology for Wellhead Protection Area Delineation (Hypothetical Ground-water Basin in Fractured Rock)



SOURCE: Modified from Otton, 1981

NOT TO SCALE

Figure 2-10
Terminology for Wellhead Protection Area Delineation (Hypothetical Confined Aquifer in Porous Media)



NOTE: ZOI is larger than area of downward leakage.

LEGEND:
- Direction of Water Flow
- Contaminant Flow
- ZOI Zone of Influence
- Water Table

NOT TO SCALE

SOURCE: Everett, 1987.

CHAPTER 3

DELINEATION CRITERIA

As discussed in the first chapter, the SDWA Amendments refer to "factors" that may be reflected in this guidance to the States (Section 1428(e)):

> Such guidance may reflect such factors as the radius of influence around a well or wellfield, the depth of drawdown of the water table by such well or wellfield at any given point, the time or rate of travel of various contaminants in various hydrologic conditions, distance from the well or wellfield, or other factors affecting the likelihood of contaminants reaching the well or wellfield.

Many of these factors have been used in Europe and by State and local agencies in the United States to protect wellheads against different types of threats, including:

- Direct introduction of contaminants into well casings
- Microbial contamination
- Chemical contamination.

This chapter focuses on a discussion of these factors, here termed "criteria" because they can be used as conceptual standards on which to base the actual delineation of a WHPA. A distinction is made between the terms "criteria" and "criteria thresholds." In using a criterion for WHPA delineation, a value or set of values must be selected to represent the limits above or below which a given criterion will cease to provide the desired degree of protection. Throughout this document these values are referred to as "criteria thresholds." Definitions and examples to clarify this distinction are provided in a later section. Later sections also provide guidance on the selection of criteria and criteria thresholds. Chapter 4 will describe how criteria and criteria thresholds can be mapped using specific techniques or methods.

3.1 CRITERIA DEFINITION AND CHARACTERISTICS

The term "criteria" is used in this document to group all conceptual standards that form the technical basis for WHPA delineation. In this chapter, five types of criteria are identified and described:

- Distance
- Drawdown

- Time of travel
- Flow boundaries
- Assimilative capacity.

It is important to note that the SDWA language of protecting WHPA's from "contaminants which may have any adverse effect on the health of persons" may be met in many ways by the State. The selection of WHP criteria and methods is only one input to this analysis of WHP Program "adequacy."

A State's choice of a criterion will likely be based on a combination of technical and nontechnical (e.g., administrative) considerations. The technical merits of a criterion depend on the degree to which a criterion incorporates the processes affecting ground-water flow and contaminant transport. For example, as shown in Figure 3-1, a criterion such as "drawdown" considers solely the physical process controlling contaminant movement due to ground-water flow (advection). Other technical criteria such as time of travel (TOT) can consider more processes, such as advection, hydrodynamic dispersion, and solid-solute interaction.

In some instances, nontechnical considerations (such as a State's institutional capabilities to implement a program) would dictate the choice of criteria. This could mandate use of a simpler criterion, such as distance, rather than a more technically sophisticated one that might be more suitable if the capability existed to implement it.

3.1.1 Distance

The distance criterion is the concept of delineating a WHPA using a radius or dimension measured from a pumping well to a point of concern. Any WHPA criterion selected must eventually be mapped. The distance criterion is the most direct way of delineating a WHPA. Since by definition a WHPA is an area, mapping it would require that a selected distance be measured from the well to the point of concern. The use of a distance criterion by itself may present a disadvantage, since it does not directly incorporate the processes of ground-water flow or contaminant transport. Therefore, the resulting WHPA could provide insufficient or ineffective protection. The latter condition might be a consequence of trying to administer an inappropriate WHPA with limited resources for contaminant source control.

Selection of distance as a criterion generally has been based on past experience with ground-water pollution control, or on nontechnical considerations. Commonly, it is an arbitrary policy decision. Distance has frequently been selected as a "first step" in WHPA

Figure 3-1
Relationship Between WHPA Delineation Criteria and Physical Processes

CRITERIA / PHYSICAL PROCESS	DISTANCE	DRAWDOWN	TOT	FLOW BOUNDARIES	ASSIMILATIVE CAPACITY
ADVECTION		●	●	●	
HYDRODYNAMIC DISPERSION (MECHANICAL DISPERSION AND MOLECULAR DIFFUSION)			●		●
SOLID-SOLUTE INTERACTION (ADSORPTION, CHEMICAL REACTIONS)			●		●

delineation; it offers significant advantages over the absence of a WHPA. Further refinement of the WHPA's may later be based on a more sophisticated or tailored criterion. Distance has been used for "generic" delineation of microbial protection zones, and for establishing setbacks from pesticide applications.

3.1.2 Drawdown

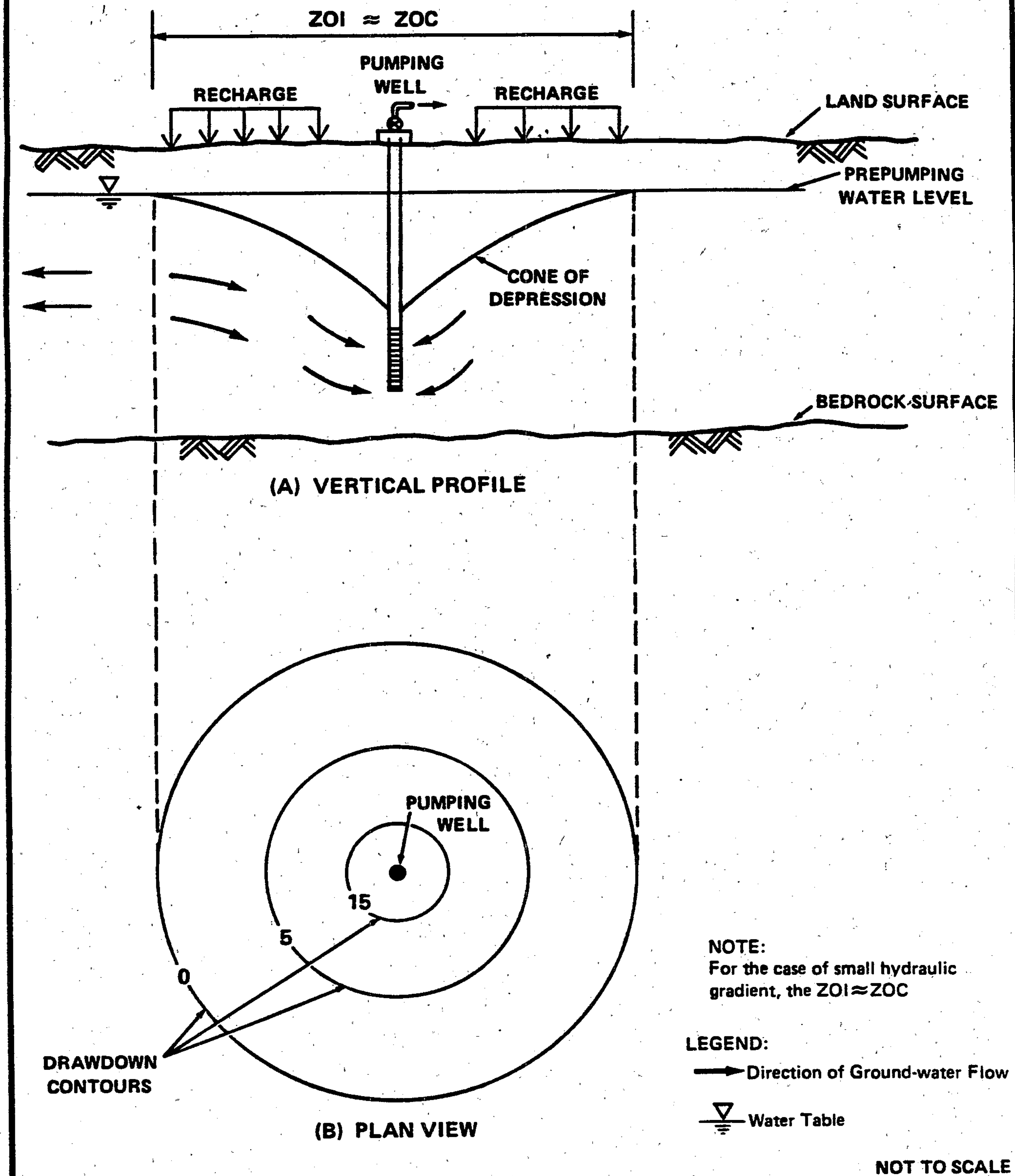
Drawdown refers to using, as the WHPA criterion, the extent to which well pumping lowers the water table of an unconfined aquifer, or the potentiometric surface of a confined aquifer. This is the criterion that defines the commonly used "cone of depression" or "area of influence" concept. As discussed in Chapter 2, the greatest drawdown occurs at the well, and decreases with distance, until a point is reached where the water level is not affected by the pumpage. This is illustrated conceptually in Figure 3-2. As a result of the drawdown created by a pumping well, the hydraulic gradients and ground-water flow velocities toward the well increase. Drawdown can accelerate contaminant migration toward a well. The actual extent of the ZOI can vary enormously, from a few tens of feet in highly prolific water-table aquifers to tens of miles in confined, consolidated, regional aquifers.

An approach to protecting the wellhead is to delineate the boundaries of the area of pumping influence (ZOI). This can be accomplished by selecting a small threshold value for a drawdown criterion and then determining the distances from the well(s) to the points where the specified criterion is satisfied. For example, in the flat water table condition shown in Figure 3-2, the ZOI is likely to coincide with the zone of contribution (ZOC). Therefore, protecting the ZOI would achieve a degree of protection similar to the results of protecting the entire ZOC. As noted earlier, however, the more common setting of a sloping water table implies a potentially significant difference between the ZOI and ZOC. Reliance on the ZOI may therefore lead to inappropriate protection in many settings.

3.1.3 Time of Travel (TOT)

TOT is a WHPA delineation criterion based on the maximum time for a ground-water contaminant to reach a well. As shown by Figure 3-1, TOT conceptually incorporates a more comprehensive evaluation of the physical processes of contaminant transport than most of the other criteria identified. Of these physical processes, advection is the best understood, and hence TOT calculations for WHPA delineation have usually been carried out on this basis. If only advection is considered, the time required

Figure 3-2
Aquifer with Flat Water Table and High Rainfall Conditions, Where Boundaries of ZOI and ZOC Approximately Coincide (Conceptual)



for a contaminant to reach a well would be affected not only by the distance to the well but also by the increase in hydraulic gradient near the well.

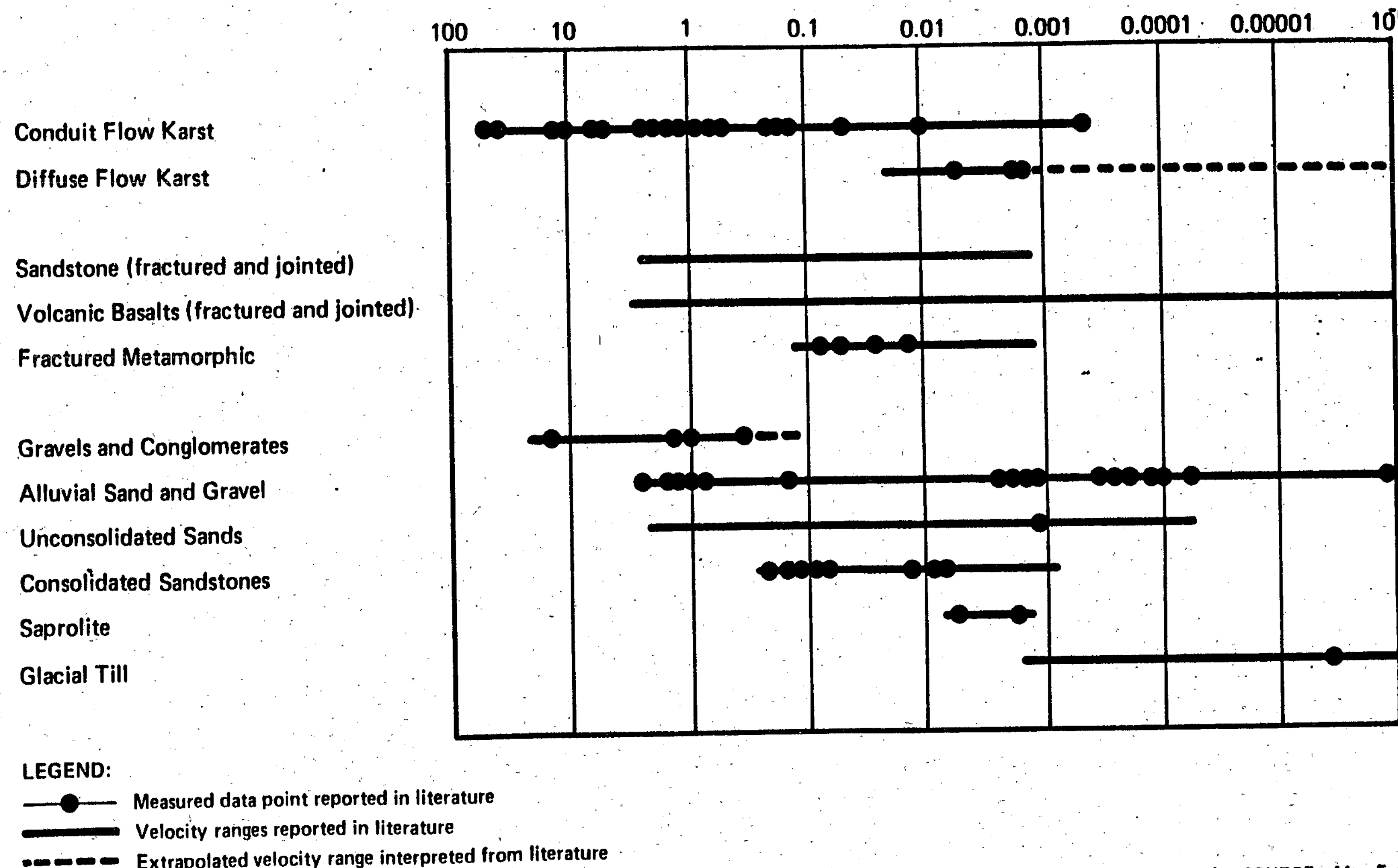
For most well fields, particularly those where flow velocities are relatively high, advection accounts for most of the movement of contaminants toward the well(s). In aquifers where the velocities are high, it is likely that a contaminant would travel quickly toward the well(s). Relatively high threshold values for a TOT criterion may be selected in these cases if possible, though some concerns over implementability may be raised.

For aquifers with low flow velocities, other physical processes, such as hydrodynamic dispersion, should be considered. Under such conditions, dispersion becomes more important, since it can cause a contaminant to reach a well sooner than would be predicted by the hydraulic TOT equation shown above. Detailed discussions on the effects of dispersion on contaminant transport can be found in Anderson (1984), Bear (1979), and Fried (1975). In addition, the concept of "facilitated transport" presented in Chapter 2 may further reduce the actual travel time of contaminants to the well. Dispersion and facilitated transport provide further scientific evidence that short TOT thresholds (based on uncontaminated ground-water flow rates) may be problematic.

TOT is an operational measure of overall ground-water flow velocities. Such velocities vary enormously based on hydrogeologic setting. Selected examples depicting this link are shown in Figure 3-3. It is apparent that, first, there is great similarity in hydraulic conductivities in a variety of types of porous granular aquifers, and second, very high flow rate environments--in fractures, solution-enlarged fractures, boulder conglomerates, and fractured volcanic rocks and lava tubes--function effectively as either open- or closed-channel (pipe) flow. In the geologic settings for such high flow velocities, which operate under peak conditions for only short periods of maximum recharge, travel times are extremely rapid. For the entire flow system, they are in terms of hours to days or weeks, rather than the years and multiples thereof characteristic of laminar flow in porous, granular aquifers. Whether confined or unconfined, the high-flow-velocity geologic settings require separate consideration from those appropriate to either consolidated or unconsolidated porous, granular media.

As a result of the focus on only maximum velocities of contaminant transport, the numerous factors operating along the contaminant's flow path (into as well as within the aquifer) to reduce, disperse, or dilute the maximum concentration become factors of

Figure 3-3
Flow Velocity Ranges



SOURCE: After Everett, 1987.

safety for the vast majority of contaminants. The consequence is that arrival times may be more accurately estimated than contaminant concentrations.

3.1.4 Flow Boundaries

A WHPA delineation criterion based on flow boundaries applies the concept of using determined locations of ground-water divides and/or other physical/hydrologic features that control ground-water flow. Use of flow boundaries as a criterion follows from the approach of protecting the well's ZOC. This assumes that a contaminant entering the ZOC would eventually reach the well under the prevailing hydraulic gradient. Examples of surface features that in some hydrogeologic settings act as flow boundaries are ridges, rivers, canals, and lakes. The limits of an aquifer and a fixed regional ground-water divide are examples of subsurface boundaries, as illustrated in Figure 3-4. This criterion is also useful for initial delineation of WHPA's for fractured bedrock and conduit-flow karst aquifers. As noted in Chapter 2, however, flow beneath surface waters due to pumping can occur. In such circumstances, the flow boundaries criterion is much less relevant.

The flow boundaries criterion is especially useful for small aquifer systems, where TOT to the boundaries may be very brief, or where the ZOI created by well pumping is rapidly affected by proximity to the physical limits of the aquifer. Moderate to larger aquifers, with boundary separations of tens to hundreds of miles, may be less amenable to this criterion due to problems of implementing protection over very large geographic areas. Exceptions should be expected, however, such as where the well is situated relatively close to these boundaries.

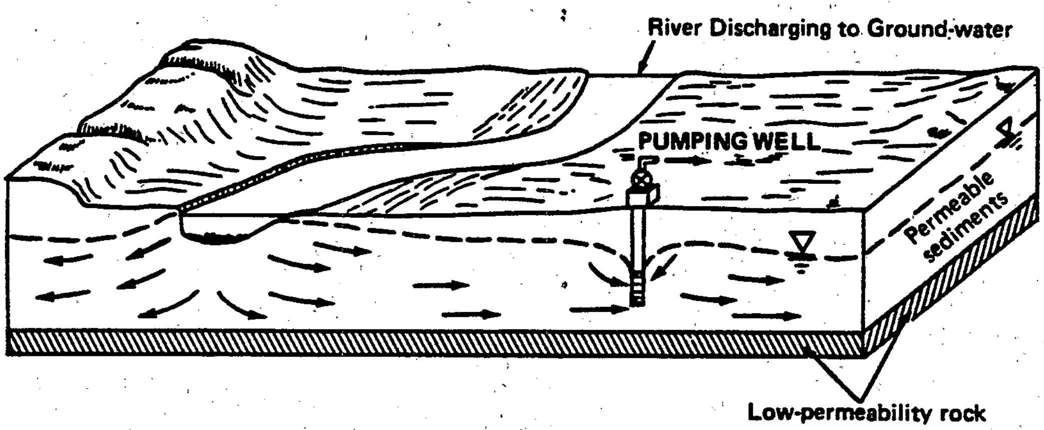
3.1.5 Assimilative Capacity

The assimilative capacity criterion for WHPA delineation applies the concept of using the ability of the saturated and/or unsaturated zones of a formation to attenuate the concentrations of contaminant(s) to acceptable levels before they reach a well.

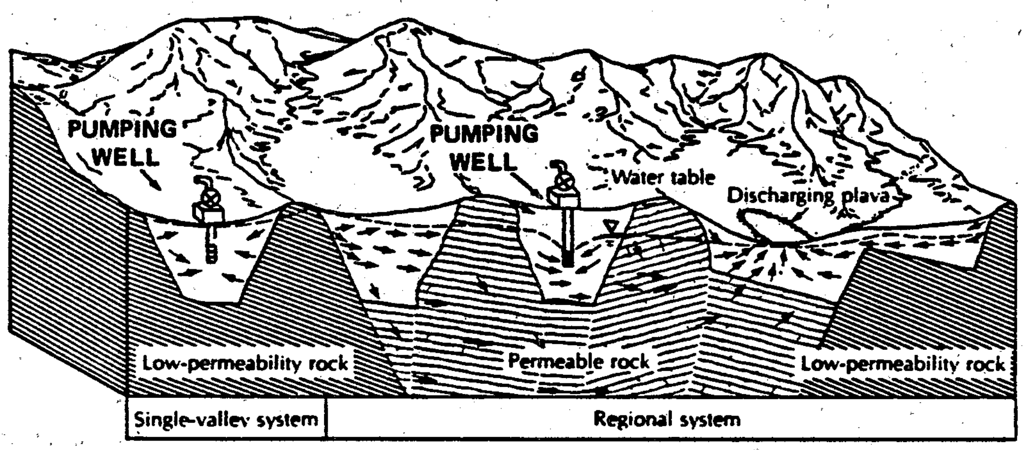
A hypothetical illustration of how the assimilative capacity of a subsurface formation could be used as a criterion in WHPA delineation is shown in Figure 3-5. The figure indicates that the subsurface formation will attenuate concentrations of contaminants generated by continuous sources located at points (1) and (2). By the time these contaminants reach the well, a desired standard or "threshold concentration" (C_a) would be satisfied.

Figure 3-4
Flow Boundaries Criteria (Conceptual)

(a)



(b)



NOTE:

(a) The ground-water divide induced by the river is an example of the type of surface feature that may be used as a physical boundary criterion [Figure (a) modified from Driscoll (1986)].

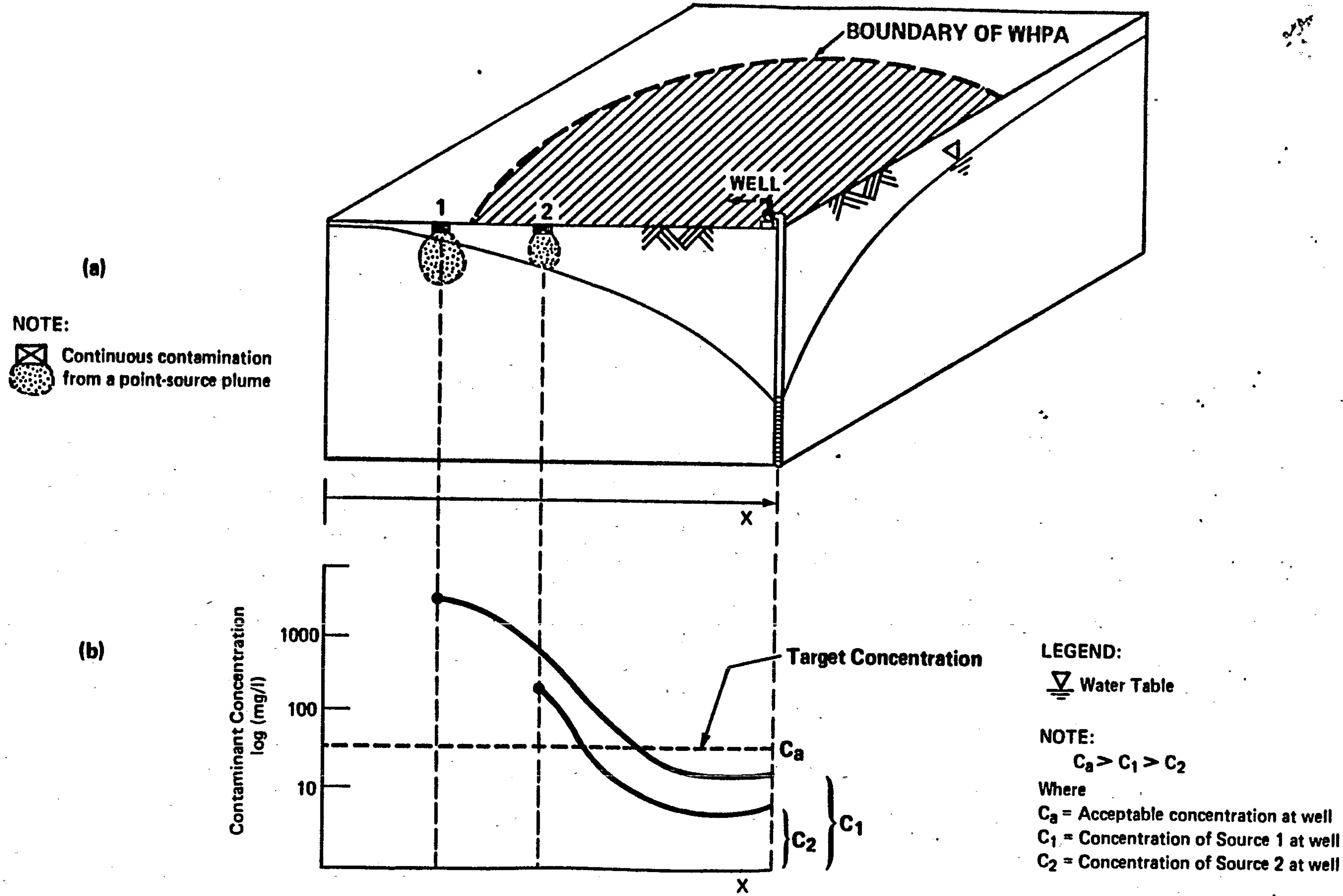
(b) The boundary between the "single valley system" and "the regional system" is an example of the type of subsurface feature that may be used as a physical boundary criterion [Figure (b) modified from Fetter (1980)].

∇ Water Table

⟶ Direction of Ground-water Flow

NOT TO SCALE

Figure 3-5
Assimilative Capacity Criteria (Conceptual)



There are no known examples of the use of an assimilative capacity criterion to delineate a WHPA for a wide range of contamination threats. The existence and the kinetics of attenuation processes are closely tied to specific contaminants and soil and aquifer matrix composition and conditions. They are not easily modeled or quantitatively determined. Site-specific data for particular contaminants are needed for evaluations; for most contaminants, little specific information on reactions is available. As a result, the attenuation mechanisms are generally considered too complex for selection as WHPA criteria. The degree to which they retard contaminant transport rates or diminish concentrations becomes an unstated factor of safety in some methods of WHPA delineation, however.

Where contamination threats are limited to one or two types, there have been some attenuative-capacity analyses. Examples include evaluations of nitrate loadings from septic tanks in certain northeastern U.S. communities, and buffer zone concepts for guarding against Aldicarb contamination in Florida.

3.2 CRITERIA THRESHOLD EXAMPLES

Development of a WHP Program will require that one or more of the WHPA delineation criteria discussed above be selected. In addition, a threshold value, or a set of them, must be chosen to implement the actual protection area delineation. Thresholds may be chosen for all three categories of threats (direct, microbial, and chemical), though the first two are often combined. A threshold value selected to implement an appropriate criterion that is overly or insufficiently conservative might not achieve the WHP goals.

This subsection presents examples of threshold values that have been used by national, state, regional, and local governing bodies. Tables 3-1 through 3-4 present threshold values for distance, drawdown, TOT, and physical boundaries criteria, respectively. The information is presented for illustrative purposes only, though it does indicate the range of thresholds that are currently being examined. In general, protection from chemical threats is being reviewed over the following criteria threshold ranges:

- TOT--5 to 50 years (within the aquifer); less than 5 years in high-flow settings
- Distance--1,000 feet to more than 2 miles
- Drawdown--0.1 to 1.0 foot
- Flow Boundaries--Physical and hydrologic

TABLE 3-1

Distance: WHPA Criterion Threshold Values

Range of Threshold Values for WHPA Criteria (ft)	Rationale	Locality	Brief Description of Hydrogeologic Setting	Example of Maximum Distance of WHPA Boundary from Well (ft)	Pumping Rate (gpm)	Reference (after Table 3-4)
2,500 (fixed circle)	"...to be sure that the zone of contribution...would be protected until the upcoming study has been completed..."	Edgartown, MA	Thick deposits of stratified glacial drift. Coastal Plain geologic province.	2,500	700	6
1,320 2,640 3,960 5,280 (fixed circles)	"...provide a means to quickly focus attention on special use, provide a protected buffer to dilute contaminants which flow into it and reduce the administrative complexities and expenses associated with delineation."	State of Pennsylvania (proposed)	Seven geologic provinces. Heavily folded and fractured sedimentary rocks in the eastern half of State grading to thinly bedded horizontal sedimentary rocks in western half. The northern border is covered by thin layers of glacial till and the southeast chiefly by foliated metamorphic units.	1,320 2,640 3,960 5,280	<7 7-35 35-69 >69	7
1,000 (fixed circle)	Same threshold used for other purposes.	Nebraska	Three geologic provinces. Extensive alluvial aquifers in west and central NE. Buried valley and sandstone aquifers in east NE.	1,000	Irrespective of Q	
6,563 (2 km) (fixed circle)	"The distance orginates from past experience in the industry, that no pollution effects had been found originating at larger distances (Zone III A)."	W. Germany	Varying hydrogeologic conditions and depths to water. Fractured sandstone and limestone aquifers frequently connected to surface water. Unconsolidated aquifers in valleys.	6,563	Irrespective of Q	2
10,560 (2 miles) (circular)	"...indicates the distance contaminants could be expected to move in problem concentrations should they be accidentally introduced into the ground-water system."	United States (EPA Classification Review Areas)	Can be expanded depending on specific hydrogeologic considerations (e.g., high ground-water velocities). water velocities).	10,560	Irrespective of Q	10

TABLE 3-2

Drawdown: WHPA Criterion Threshold Values

Range of Threshold Values for WHPA Criteria (ft)	Rationale	Locality	Brief Description of Hydrogeologic Setting	Example of Maximum Distance of WHPA Boundary from Well (ft)	Pumping Rate (gpm)	Reference (after Table 3-4)
0.25 (for westerly boundary)	"...the protection area west of the turnpike is defined by the quarter-foot (0.25) drawdown, as compared to easterly boundary...which is determined by water divide." "The selection of this protection area...was based on the rationale that land should not be released for incompatible development in the short run that would later have to be reincorporated into the regulatory boundaries."	Dade County, FL	Biscayne Aquifer is composed in most part by solution-riddled limestone, sandstone, and sand. It is a highly permeable wedge-shaped unconfined aquifer. Recharged by local precipitation and canals.	23,000	104,000 (northwest well field)	4
1.0	Suitable for field monitoring.	Palm Beach County, FL	Eastern part of County is considered an extension of the Biscayne Aquifer (see Dade). Sediments consisting of a sequence of unconsolidated sands, loose- to well-cemented limestones. An intricate system of canals controls ground-water levels in the area.	10,500 ft	28,000 (Boynton Beach well field)	8

TABLE 3-3

Time of Travel: WHPA Criterion Threshold Values

Range of Threshold Values for WHPA Criteria (days)	Rationale	Locality	Brief Description of Hydrogeologic Setting	Example of Maximum Distance of WHPA Boundary from Well (ft)	Pumping Rate (gpm)	Reference (after Table 3-4)
50 (Zone I, TOT Criteria)	"the time required to ensure the natural or appreciable reduction in microbial organisms."	Southern England	All deposits are sedimentary. Eighty-two (82) percent of all ground water pumped is derived from chalk. The chalk is a very fine-grained fissured white limestone. Ground-water movement is mainly by fissure-flow and is enhanced by solutioning.	8,200	2,750 (for large well fields in chalk)	1
50	"...protection exerted was against pathogens (bacteria and viruses) and rapidly degradable chemicals."	The Netherlands	A continuously sinking basin in which sedimentation of marine and fluvial sands and clays has taken place. Flat topography and only locally hilly. Little faulting. Mainly uniform, horizontally layered aquifers of unconsolidated sands and clays. Ground-water flow is laminar with velocities ranging from 10-100 m/yr (33-330 ft/yr).	500	1,500 (average well field)	2
100 (Zone IV)	"...is based on the information which was found in the literature concerning enteric viruses. These viruses have been shown to survive in water and soils for an average of 100 days."	Dade County, FL	Biscayne Aquifer is composed in most part by solution-riddled limestone, sandstone, and sand. It has a highly permeable wedge-shaped unconfined aquifer. Recharged by local precipitation and canals.	5,300	104,000 (northwest well field)	3
210 (Zone V)	"...represents the longest period of time on record in which the Biscayne aquifer was not recharged by normal rainfall patterns."	Dade County, FL	(same as above)	10,000	104,000 (northwest well field)	3

TABLE 3-3 (cont'd)

Range of Threshold Values for WHPA Criteria (years)	Rationale	Locality	Brief Description of Hydrogeologic Setting	Example of Maximum Distance of WHPA Boundary from Well (ft)	Pumping Rate (gpm)	Reference (after Table 3-4)
10	"In the case of severe pollution of a persistent compound within the recharge area, an attempt must be made to repair the damage...For the sake of continuity of water supply and to exclude public health risks, a delay of ground-water in the aquifer of at least 10 years is needed..."	The Netherlands	A continuously sinking basin in which sedimentation of marine and fluviatile sands and clays has taken place. Flat topography and only locally hilly. Little faulting. Mainly uniform, horizontally layered aquifers of unconsolidated sand and clays. Ground-water flow is laminar with velocities ranging from 10-100 m per year (33/330 ft/year)	2,600	1,500 (for average well field)	2
25	"Because in many cases even 10 years will not be sufficient to guarantee continuity of safe water supply..."	The Netherlands	(same as above)	3,900	(same as above)	
10 25 50	"...to provide the town with an initial screening mechanism for evaluating the need for corrective action in the event that contamination is detected or a catastrophic spill of hazardous materials ...occurs."	Town of Falmouth, MA	Geologic formations include the Mashpee pitted outwash plain deposits, and Buzzards Bay moraine and outwash deposits. The majority of town is situated over the Mashpee pitted outwash plain.	2,500 6,500 12,500	465	2 5

TABLE 3-4

Physical Boundaries: WHPA Criterion Threshold Values

Range of Threshold Values for WHPA Criteria	Rationale	Locality	Brief Description of Hydrogeologic Setting	Example of Maximum Distance of WHPA Boundary from Well (ft)	Pumping Rate (gpm)	Reference (after Table 3-4)
Topographical and Local Ground-Water Divide	"...areas of WHPA's were outlined to encompass the inferred recharge zone to each particular ground-water source."	Vermont	--	3,500	N/A	11
Fraction of Distance (1/3) to Regional Ground-Water Divide	"...under steady state conditions there is a direct relationship between the volume of water pumped from a well and the land area comprising the Zone of Contribution (ZOC)."	Cape Cod, MA	Comprises sands, silts, clay, and gravel deposited during the late Wisconsin deglaciation. Deposits are thick, homogeneous outwash plains, and the ground-water system exist as unconfined aquifers within the unconsolidated deposits.	10,500	700	9
Full Distance to Regional Ground-Water Divide	--	Edgartown, MA	--	3,800	700	6
SCE Canal (easterly boundary)	"The computer modeling indicates that the cone-of-influence will not extend east of the SCE Canal..."	Dade County, FL (northwest well field)	Biscayne Aquifer is composed in most part by solution-riddled limestone, sandstone, and sand. It is a highly permeable wedge-shaped unconfined aquifer. Recharged by local precipitation and canals.	11,000	100,000 (northwest well field)	4

REFERENCES FOR TABLES 3-1 THROUGH 3-4

1 Southern Water Authority, 1985
2 Mathess, et al., 1985
3 Rivkin, 1984
4 Dade County Planning Department, 1985
5 Camp, Dresser & McKee, Inc., 1986
6 Anderson-Nichols & Co., Inc., 1985
7 Pennsylvania, Commonwealth of, Division of Water Quality, 1986
8 Dames & Moore, 1987.
9 Horsley and Cambareri, 1984
10 Environmental Protection Agency, 1986

- Assimilative Capacity--Single-constituent only; targeted to drinking water standards.

3.3 CRITERIA SELECTION CONSIDERATIONS

Three major considerations, shown schematically in Figure 3-6, can affect the delineation of WHPA's in a State. The relative importance of each consideration will vary from State to State. The considerations are:

- Overall protection goal(s)
- Other technical considerations
- Other policy considerations.

Policy issues are comprehensively addressed under parallel efforts by EPA. This subsection emphasizes the technical considerations and the overall protection goals that affect criteria selection. However, a brief discussion of the effects of policy issues is also included. Policy and technical considerations will not always lead to the selection of the same criterion. For example, policy considerations for a specific geologic setting may lead to the selection of distance as the criterion, while technical considerations may lead to selecting a criterion such as flow boundaries. Similarly, technical evaluations of ground-water flow may suggest TOT thresholds of 50 years or more, whereas policy considerations may favor TOT thresholds of 10 to 20 years.

3.3.1 Overall Protection Goals

As noted previously, three general goals have been identified as relevant to the process of selecting WHPA delineation criteria:

- Reaction Time. Provide a remedial action zone to protect wells from unexpected contaminant releases.
- Attenuation of Contaminants. Attenuate the concentrations of specific contaminants to desired levels at the time they reach the wellhead.
- Protect All or Part of ZOC. Provide a well-field management zone in all or a major portion of a well's existing or potential recharge area.

Relationships between the criteria and these goals, along with a brief assessment of the goals, are shown in Table 3-5.

Figure 3-6
Consideration Factors That May Affect Criteria Selection

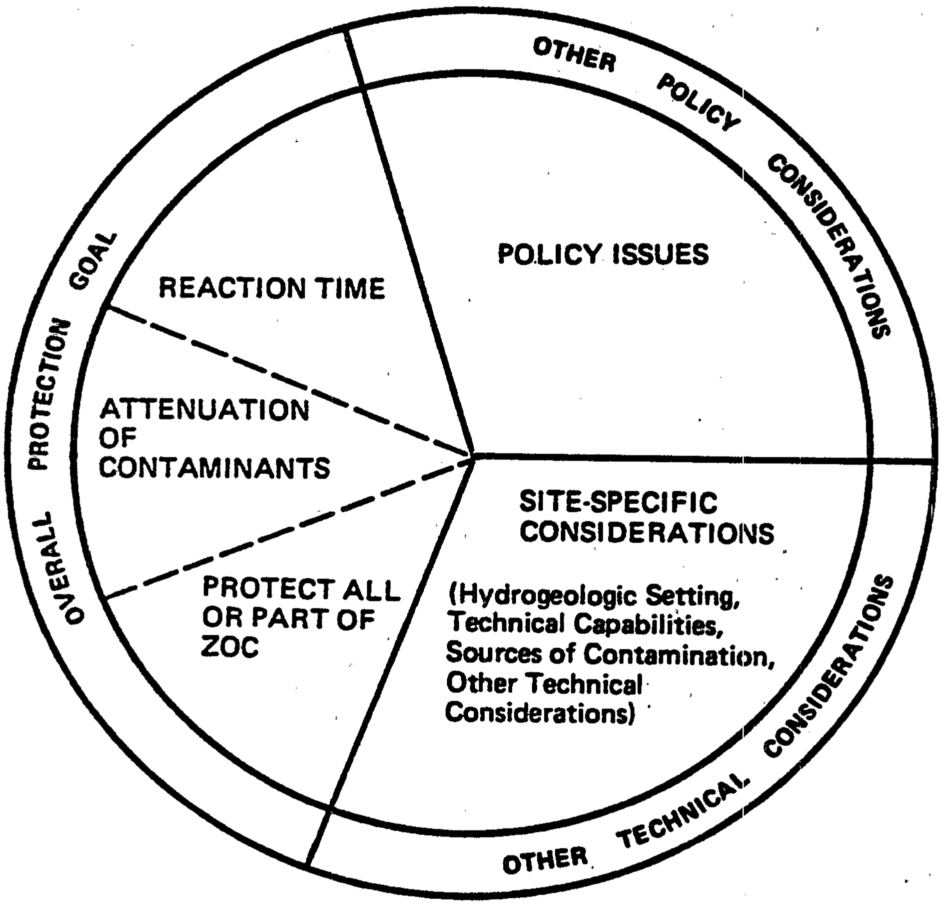


TABLE 3-5

Example Relationships Between Overall Protection Goals and Criteria for Delineating Wellhead Protection Areas

Overall Protection Goals	Examples of Corresponding Criteria	Example of Criteria Threshold	Advantages	Disadvantages	Hydrogeologic Factors	Management Factors
1. Delineate a <u>remedial action zone</u> allowing adequate reaction time to protect well from contaminant releases	TOT	5-year TOT to well (State of Florida) 10-25 year TOT (the Netherlands)	Deals directly with most threatening sources in a manner understandable to regulated community; "compatible" with existing programs	Implies capability/ success of corrective action measures at all relevant sources	High confidence in accuracy of TOT determinations at specific wellhead areas	Possible ban of all high-risk activities within WHPA; controls/ monitoring of all significant sources within recharge area, especially those beyond WHPA
2. Provide a <u>zone for attenuation</u> of contaminants to specified levels before they reach well	Assimilative capacity	Meet percentage of MCL in raw water supplying well	Most directly addresses specific contaminants of concern and "standard" in SDWA	Currently viable only for simple problems such as microbial contaminants; conservative parameters (e.g., synthetic organics) more problematic	Analysis sufficiently thorough to show that zone is extensive enough to meet target concentrations at well	Displays understanding of contamination sources, locations, contaminant characteristics, and impacts of controls
3a. Provide a <u>well-field management</u> area in major portion of recharge area	Drawdown distance	0.25-foot drawdown contour (Dade Co., FL) 2 km (W. Germany)	Broadest definition: can be tailored by States as appropriate; can incorporate other options	May lead to "over-protection" in some States; "under-protection" in others	Based on reasonable application of hydrogeologic concepts to available data	Based on reasonable consideration of relevant management factors
3b. Manage entire recharge area under current and foreseeable conditions	Flow boundaries	Physical limits of aquifer and surface drainage (some parts of Massachusetts)	Can be interpreted as most protective; especially appropriate to small aquifers (e.g., less than 10-20 square miles)	Over-protective for moderate to large aquifers	Analysis shows full recharge area under existing and potential pumping scenarios	Controls extend to all potential contamination sources within recharge area

3.3.2 Technical Considerations

This subsection identifies the technical factors that can be used to evaluate and ultimately select the delineation criteria. A matrix of technical evaluation factors versus criteria is presented as Table 3-6. The matrix cells have been left blank so that an appropriate ranking of each criterion may be made by a State or locality in the selection process. It should be noted that the relative importance of these evaluation factors depends on the hydrogeologic setting as well as the goals of the protection program in which they are applied. The technical factors are described below.

Ease of Application. A factor in evaluating a criterion is how easily a technical user can apply it. For valid WHPA delineations, the State must have technical specialists capable of implementing the delineation criteria chosen. The more technologically demanding criteria require more advanced and specialized user abilities.

Ease of Quantification. The ability to place a numerical value or threshold on a criterion has a major influence on its suitability for use in guidelines or regulations. Some criteria, such as distance and TOT, are easily expressed in numerical terms. Others, most notably assimilative capacity, are difficult to quantify. Consequently, the clarity of communicating or legally defining criterion values can vary widely.

Variability Under Actual Conditions. Another consideration is the ability of a criterion to reflect changes in hydrologic conditions. These changes may be due to pumping rates, recharge rates, and flow boundary effects, and will likely affect movement of a contaminant toward a well. For example, a criterion such as TOT will allow a user to modify the size of a WHPA to reflect an anticipated increase in pumping rates. In such case, the hydraulic gradients near a well will be increased, and the distance that a contaminant will travel in a given time (i.e., a specified criterion threshold) will also increase.

Ease of Field Verification. Often it is quite difficult to reproduce accurately in the field values that have been previously calculated. The ability to confirm criterion threshold values through onsite testing or inspection thus becomes significant in evaluating criteria for selection. For example, in a porous media aquifer it would be considerably more difficult to verify estimated TOT's than drawdowns.

Ability to Reflect Ground-Water Standards. Another consideration for selecting a WHPA delineation criterion is the potential for relating it to an overall water quality standard (in the well or ground water). For example, selecting assimilative capacity as a delineation

Table 3-6
WHPA Criteria Selection Versus Technical Considerations

TECHNICAL CONSIDERATION / CRITERIA	EASE OF APPLICATION L/M/H	EASE OF QUANTIFICATION L/M/H	VARIABILITY UNDER ACTUAL CONDITIONS L/M/H	EASE OF FIELD VERIFICATION L/M/H	ABILITY TO REFLECT GROUND-WATER STANDARD L/M/H	SUITABILITY FOR A GIVEN HYDROGEOLOGIC SETTING L/M/H	ABILITY TO INCORPORATE PHYSICAL PROCESSES L/M/H	RANK (1 TO 5)
DISTANCE								
DRAWDOWN								
TIME OF TRAVEL								
FLOW BOUNDARIES								
ASSIMILATIVE CAPACITY								

L — LOW
M — MEDIUM
H — HIGH
N/A — NOT APPLICABLE

NOTE: Ranking (1-5): 5 is most desirable, 1 is least desirable.

criterion implies that the attenuation characteristics along flow paths in the saturated and unsaturated zones are known. Knowledge of how, where, and when the concentrations of a specific contaminant are reduced would be helpful in determining whether a standard can be met.

Suitability for a Given Hydrogeologic Setting. Hydrogeologic controls over ground water vary widely under natural conditions. The ability to apply a criterion to the hydrogeologic setting being considered is, from a technical perspective, an essential evaluation factor. Among the major physical controls that may influence the appropriateness and ease of criteria application are the location of aquifer boundaries, extent of confinement, degree of consolidation, amount of fracturing, and extent of solution channel development.

Ability to Incorporate Physical Processes. Selection of a criterion should include consideration of whether the physical processes controlling contaminant transport at the specific site are incorporated by the criterion.

3.3.3 Policy Considerations

Because a parallel effort by EPA is addressing policy/management issues, this subsection will describe only a few basic policy considerations for illustration. The discussion is not intended to be comprehensive.

To aid in the process of selecting a criterion, an evaluation matrix of criteria versus policy considerations is presented as Table 3-7. The matrix cells have been left blank, so that an appropriate ranking of each criterion may be made by a State or locality in the selection process. The policy considerations in the matrix are described below. In general, it should be noted that the primary policy consideration, which cuts across the four separate considerations, is the applicability of the criterion to the overall WHP goal.

Ease of Understanding. How easily a criterion can be understood by the general public is considered to be a significant measure of its usefulness, and may affect the decision to use the criterion in a WHPA delineation program. For example, prior to establishing a delineation program, the policy of a State may be to conduct a public outreach/information program, for which purposes ease of understanding will be relevant.

Economy of Criteria Development. The economics of developing a criterion and related threshold values are also significant considerations. The costs of applying a criterion, and of developing the technical resources to support this application, may do much to inhibit or encourage its use. Generally, criteria that are highly complex, rely on a detailed data

Table 3-7
WHPA Criteria Selection Versus Policy Considerations

POLICY CONSIDERATION / CRITERIA	EASE OF UNDERSTANDING (L/M/H)	ECONOMY OF CRITERIA DEVELOPMENT (L/M/H)	DEFENSIBILITY (L/M/H)	USEFULNESS FOR IMPLEMENTING PHASING (L/M/H)	RELEVANCE TO PROTECTION GOAL (L/M/H)
DISTANCE					
DRAWDOWN					
TOT					
FLOW BOUNDARIES					
ASSIMILATIVE CAPACITY					

L–LOW
M–MEDIUM
H–HIGH
N/A–NOT APPLICABLE

base, or are labor intensive to apply will be expensive. This may deter their selection and acceptance, even though their technical validity is unquestioned.

Defensibility. Enforcement and permitting considerations will require that the boundaries of a WHPA be clearly defined and defensible against potential challenges and litigation from the parties affected by the delineation. Some criteria are more contestable in legal disputes than others. Therefore, policymakers may prefer to use the most technically defensible criteria for those areas in a State where the potential for litigation or challenge to the delineation is likely to occur.

Usefulness for Implementing Phasing. Some States may prefer to initiate their WHPA programs using the simplest and/or most economic criteria. For example, a criterion such as distance could be selected at the initial phase. The concept of "phasing" is to initiate the program in this way, moving toward more sophisticated criteria at a later time.

Relevance to Protection Goal. A final deciding factor in criteria evaluation is the degree to which specific criteria can meet or support the protection goal selected by the State. As mentioned in subsection 3.3.1, with examples in Table 3-5, these goals include providing a remedial action zone, an attenuation zone, and a well-field management zone.

CHAPTER 4

WHPA DELINEATION METHODS

This chapter describes the techniques or "methods" used to translate the selected criteria and criteria thresholds described in the previous chapter to actual, mappable delineation boundaries. Information has been assembled on the methods used in various ground-water protection programs in the United States and Western Europe to delineate WHPA boundaries. From this information, six primary methods were examined. Each has inherent strengths and weaknesses, depending upon hydrogeologic conditions and the overall goals and objectives of the WHPA program. This chapter reviews these methods and provides examples at different levels of sophistication. Since WHP is a relatively new concept, however, new methods or modifications of existing methods will undoubtedly surface in the next few years.

4.1 INTRODUCTION TO WHPA DELINEATION METHODS

The six primary methods are listed below in order of increasing technical sophistication:

- Arbitrary fixed radii
- Calculated fixed radii
- Simplified variable shapes
- Analytical methods
- Hydrogeologic mapping
- Numerical flow/transport models.

The methods range from simple, inexpensive methods to highly complex and costly ones. Table 4-1 presents the WHPA delineation methods, together with places where they have been or are being applied. In any WHP program, however, it is important to remember that more than one method can be used to delineate a WHPA for a single well or well field.

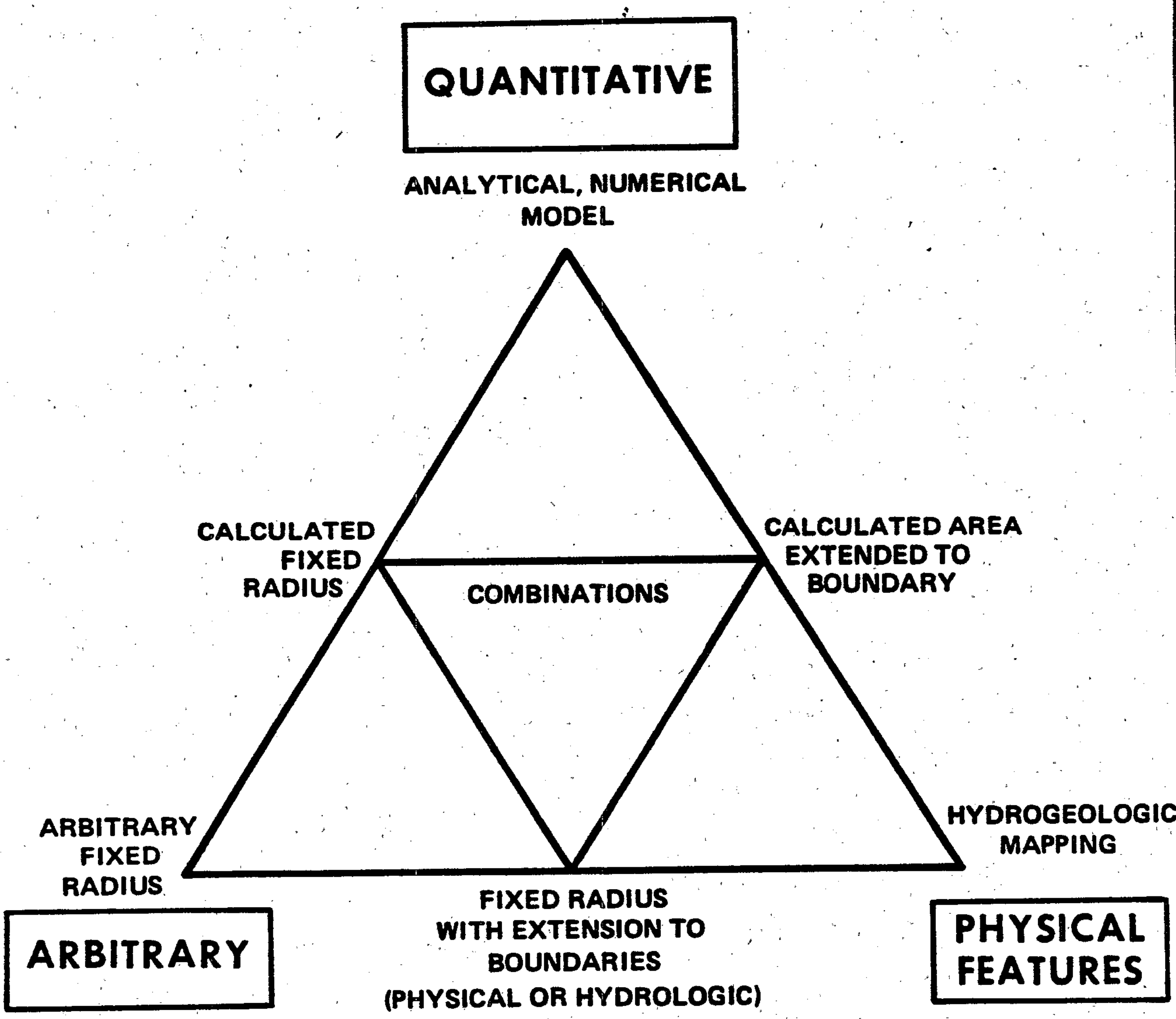
The various methods of delineating WHPA's can be represented conceptually in a triangular diagram, Figure 4-1. The vertices (three corner points) represent pure applications of the three major method types. These allow a range in sophistication--from the selection of arbitrary values (e.g., a simple fixed radius with no scientific basis), to the application of highly quantified techniques (e.g., analytical and numerical models based on extensive site-specific data), to mapping physical features which determine the

TABLE 4-1

WHPA Delineation Methods and Example Applications

Method	Example Locations Where Used
Arbitrary Fixed Radii	Nebraska Florida Cape Cod, Massachusetts
Calculated Fixed Radii	Florida Vermont
Simplified Variable Shapes	Southern England
Analytical Methods	Cape Cod, Massachusetts West Germany Holland
Hydrogeologic Mapping	Vermont Connecticut Cape Cod, Massachusetts
Numerical Flow/Transport Models	Southern Florida Cape Cod, Massachusetts

Figure 4-1
Interrelationships of WHPA Methods



geologic or geomorphic controls on ground-water flow. Intermediate methods lie somewhere between these three "corners."

WHPA's delineated by a calculated radius based on generalized regional flow equations would be a combination of arbitrary and quantitative methods. Regional flow models can be developed and used by combining the quantitative and physical features methods. An approach that starts with a fixed radius and then extends the area to a basin divide would combine the arbitrary and physical features methods. Numerous permutations can be developed by combining the methods represented by the endpoints.

4.2 WHPA DELINEATION METHOD ASSESSMENTS

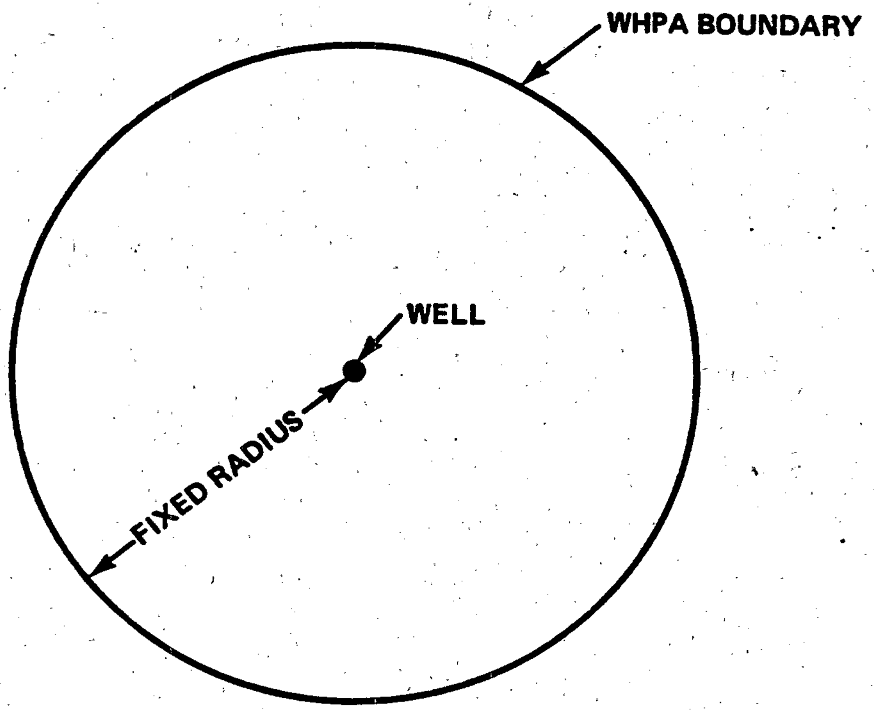
Various aspects and specific examples of the WHPA delineation methods are discussed in the following subsections. Brief indications of the costs involved in implementation and application of each method are presented here, though more quantitative cost estimates are provided in Section 4.3.

4.2.1 Arbitrary Fixed Radii

Delineation of a WHPA using the arbitrary fixed radii method involves drawing a circle of a specified radius around a well being protected. The radius of the WHPA may be an arbitrarily selected distance criterion threshold value (Figure 4-2). Although it may appear that protection areas delineated by this method are not based on scientific principles, the distance criteria threshold may be based on very generalized hydrogeologic considerations and/or professional judgement. For example, the distance threshold selected--the radius or set of radii--could be based on averaging the distances which correspond to a TOT threshold under various hydrogeologic settings across the State.

Advantages. The arbitrary fixed radii method is an easy technique for applying a distance criterion, can be very inexpensive, and requires relatively little technical expertise. Using this method, WHPA's for a large number of wells can be delineated in a relatively short time. The approach can be protective if large thresholds are chosen, overriding somewhat its lack of hydrogeologic precision. The method can also be used to initially define WHPA's until a more sophisticated approach can be adopted, as the need for accurate protection increases or more hydrogeologic data become available. The concept of gradually implementing more sophisticated approaches is called "phasing" in this document.

Figure 4-2
WHPA Delineation Using the Arbitrary Fixed Radius Method



NOT TO SCALE

Disadvantages. A high degree of uncertainty complicates the application of the arbitrary fixed radii method, due to the lack of scientific basis for the criteria threshold values used with the method. This can be particularly true in areas of heterogeneous and non-isotropic hydrogeology or where significant hydrologic boundaries are present. This method may also tend to over- or under-protect well recharge areas. This could add to costs of procuring or controlling land use in areas that aren't needed. Conversely, recharge areas that should be protected may lie outside of the fixed radius, and thus outside the protection area. If large thresholds are chosen, however (perhaps 2 or more miles), a significant amount of protection could be afforded in most settings.

Costs. The costs of developing and implementing a WHPA program using the arbitrary fixed radii method are relatively low. A minimum amount of data collection is required to draw a circular WHPA based on a distance criterion threshold. In addition, WHPA's can be delineated for a large number of wells in a relatively short time.

4.2.2 Calculated Fixed Radii

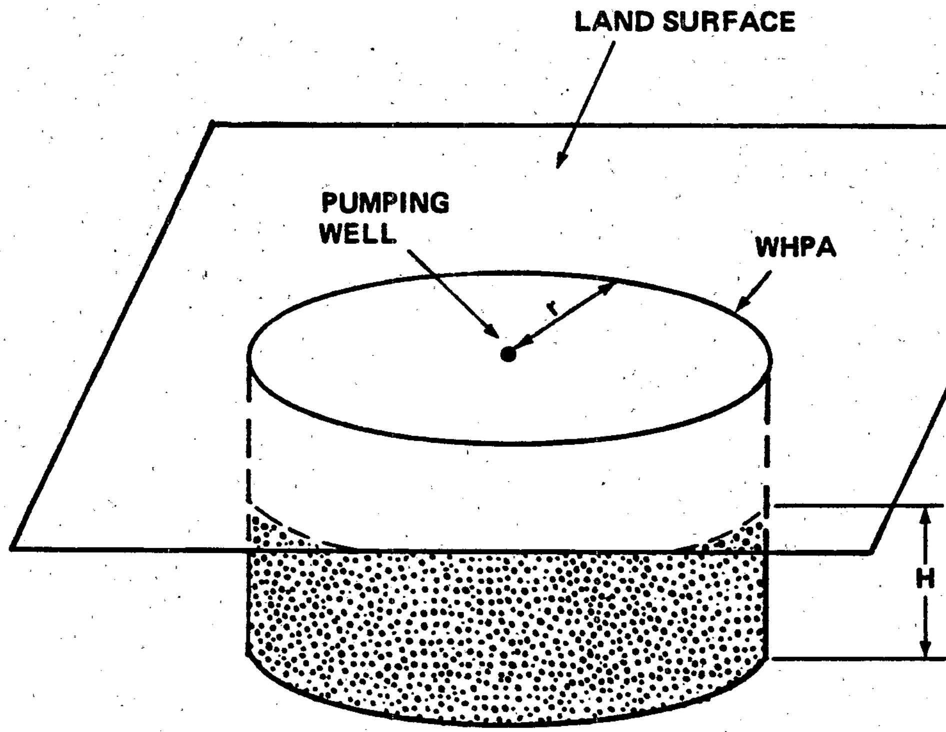
Delineation of a WHPA using the calculated fixed radii method involves drawing a circle for a specified TOT criterion threshold. A radius is calculated using an analytical equation that is based on the volume of water that will be drawn to a well in the specified time (Figure 4-3).

The input data required by the equation includes the pumping rate of the well and hydrogeologic parameters such as porosity and hydraulic conductivity. The time period used is one considered adequate to allow cleanup of ground-water contamination before it reaches a well, or that allows adequate dilution or dispersion of contaminants.

Advantages. The method is easy to apply and relatively inexpensive; it requires a limited amount of technical expertise. In addition, WHPA's can be delineated for a large number of wells in a short period of time. Conceptually, it offers a significant increase in WHPA-specific accuracy over the fixed-radius method. However, this approach requires more money than using arbitrary fixed radii, since time and costs may be greater, and data must be developed to define the criteria thresholds and parameters used in the equation.

Disadvantages. The calculated fixed radii method may be inaccurate, since it does not account for many factors that influence contaminant transport. This can particularly be true in areas of heterogeneous and non-isotropic hydrogeology or where significant hydrologic boundaries are present.

Figure 4-3
WHPA Delineation Using the Calculated Fixed Radius Method



-Radius (r) is calculated using a simple equation that incorporates well pumping rate and basic hydrogeologic parameters.

-Radius determines a volume of water that would be pumped from well in a specified time period.

H = Open interval or length of well screen.

NOT TO SCALE

Costs. Costs of developing and implementing a WHPA program using calculated fixed radii are relatively low. Some initial costs may be encountered in developing the criteria thresholds and in hydrogeologic data collection. The costs of actually mapping the WHPA's thereafter, however, is relatively low, in that a large number of WHPA's can be delineated with a small investment of time. In general, the calculated fixed radius method is more expensive than the arbitrary fixed radius method, because of more extensive data requirements.

Example 1: Florida. The Florida Department of Environmental Regulations (FDER) requires that Zone II of a WHPA be defined as a circle of a radius (r) calculated using a volumetric equation with a 5-year time of travel criterion. Figure 4-4 shows the FDER equation and an application to a well in the Biscayne aquifer in Florida. The volumetric equation is shown on the figure.

Example 2: Vermont. As an additional example, Vermont used a calculated fixed radius equation to delineate WHPA's based on a drawdown criterion threshold of 0.05 foot (Vermont Department of Water Resources, 1985). If pump test data are available for an unconfined unconsolidated aquifer, then the radius of the primary zone of protection is determined using the Theis nonequilibrium equation (Theis, 1935)

$$r = \sqrt{\frac{u4Tt}{S}}$$

Where
- T = aquifer transmissivity
- t = time to reach steady state
- S = storativity or specific yield of aquifer

and u is a dimensionless parameter related to the well function

$$W(u) = \frac{4\pi Ts}{Q}$$

Where
- s = drawdown at the maximum radius of influence
- Q = pumping rate

To calculate the radius, the well function is calculated and u is obtained from a table. This value of u is then used to calculate the radius.

In the case of an aquifer in Vermont, the input data are

$T = 200\ ft^2/day$

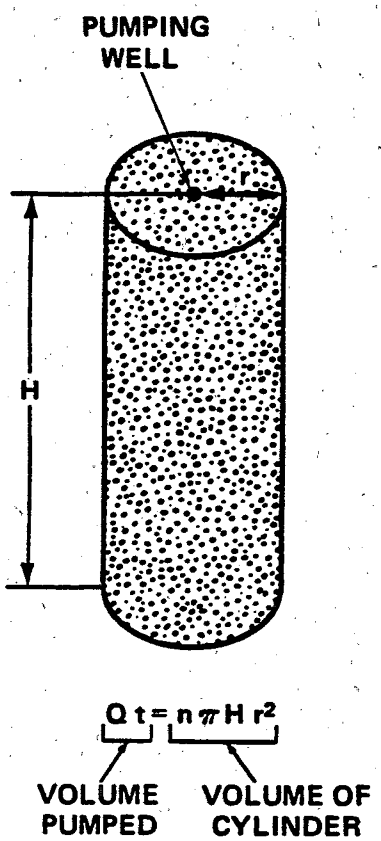
$t = 1\ day$

$S = 0.02$

$Q = 25\ gpm$

$s = 0.05\ feet$

Figure 4-4
WHPA Delineation Using FDER Volumetric Flow Equation for Well in Florida



$$r = \sqrt{\frac{Q\,t}{\pi\,n\,H}} = 1138 \text{ ft}$$

WHERE

Q = Pumping Rate of Well = 694.4 gpm = 48,793,668 ft^3/yr

n = Aquifer Porosity = 0.2

H = Open Interval or Length of Well Screen = 300 ft

t = Travel Time to Well (5 Years)

(Any consistent system of units may be used.)

and the radius of the primary protection zone is 315 feet. To provide a more accurate WHPA, this calculated radius is then skewed in the direction of ground-water flow patterns.

4.2.3 Simplified Variable Shapes

In the simplified variable shapes method, "standardized forms" are generated using analytical models, with both flow boundaries and TOT used as criteria. This method attempts to simplify implementation by selecting a few representative shapes from the large array of potential possibilities. The appropriate "standardized form" is then selected for hydrogeologic and pumping conditions matching or similar to those found at the wellhead (Figure 4-5). The standardized form is then oriented around the well according to ground-water flow patterns. The variable shapes are calculated by first computing the distance to downgradient and lateral extents of the ground-water flow boundaries around a pumping well (i.e., the ZOC), and then using a TOT criterion to calculate the upgradient extent. Standardized forms for various criteria are calculated for different sets of hydrogeologic conditions. Input data for the standardized shapes include basic hydrogeologic parameters and well pumping rates.

Advantages. Advantages of the simplified variable shapes method are that it can be easily implemented once the shapes of the standardized forms are calculated, and that it requires a relatively small amount of field data. In addition, relatively little technical expertise is required to do the actual delineations. Generally, the only information required to apply the shapes to a particular well or well field, once the standardized forms are delineated, are the well pumping rate, material type, and the direction of ground-water flow. This method offers a more refined analysis than the fixed-radius method, with only a modest increase in cost.

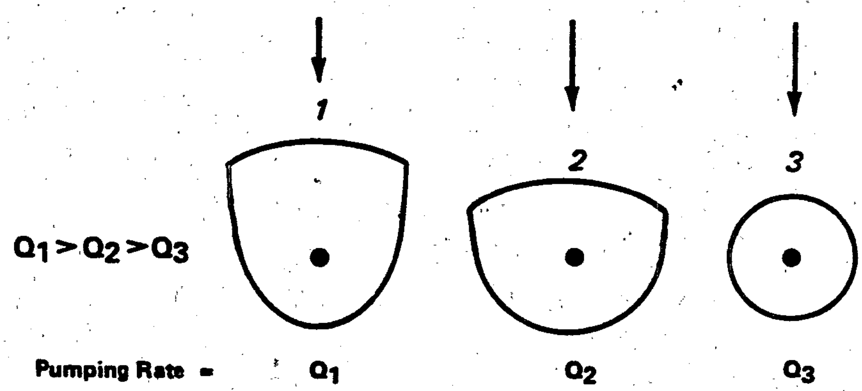
Disadvantages. The simplified variable shapes method may not be accurate in areas with many geologic heterogeneities and hydrologic boundaries. There are some conceptual problems if flow directions near a well differ from those inferred from regional or subregional assessments.

Costs. Costs of initially developing the standardized forms for a specific State or locality may be moderate, although the costs of implementation (i.e., selecting the appropriate standard shape for a well site) are relatively low. Significant data collection is required (compared to calculated fixed radii) in order to obtain the set of representative hydrogeologic parameters needed to calculate the shapes of the standardized forms and to determine the overall ground-water flow directions in the vicinity of specific wells.

Figure 4-5

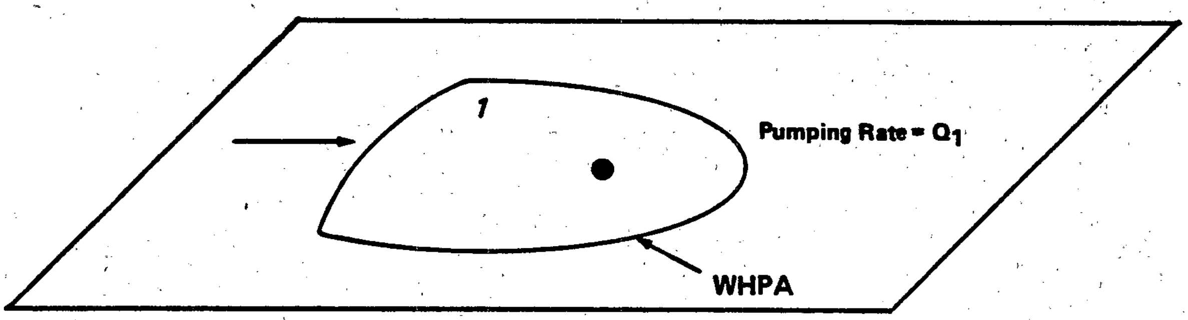
WHPA Delineation Using Simplified Variable Shapes Method

STEP 1: DELINEATE STANDARDIZED FORMS FOR CERTAIN AQUIFER TYPE



- Various standardized forms are generated using analytical equations using sets of representative hydrogeologic parameters.
- Upgradient extent of WHPA is calculated with TOT equation; downgradient with uniform flow equation.

STEP 2: APPLY STANDARDIZED FORM TO WELLHEAD IN AQUIFER TYPE



- Standardized form is then applied to well with similar pumping rate and hydrogeologic parameters.

LEGEND:

● Pumping Well

↓ Direction of Ground-water Flow

NOT TO SCALE

Example: Southern England. In England, the shapes of "standardized forms" used in the simplified variable shapes method are developed using uniform flow equations (Todd, 1980) and a TOT equation. The concern in Southern England is protection of the highly prolific, high-flow Chalk aquifer. Areas are generated for various sets of representative hydrogeologic conditions. The standardized forms are then oriented around the well according to ground-water flow patterns (Southern Water Authority, 1985).

The uniform flow equations (subsection 4.2.4) are used to calculate the zone of contribution to a pumping well. These equations describe the ZOC for a confined, porous media aquifer under uniform flow and steady-state conditions. For unconfined aquifers, thickness is replaced by the uniform saturated aquifer thickness, provided that the drawdown at the well is small in relation to the aquifer thickness. These equations do not determine the upgradient limits of the ZOC. Therefore, another technique is necessary to close the upgradient boundary of the ZOC. The Southern Water Authority in England utilizes a TOT equation.

The distance (r_x) defining the upgradient extent of the ZOC is determined by substituting a 50-day TOT criterion for t_x and solving by trial and error the equation

$$t_x = \frac{S}{v}\left[\pm (r_x - r_w) + Z \ln \frac{(Z \pm r_w)}{(Z \pm r_x)}\right]$$

where

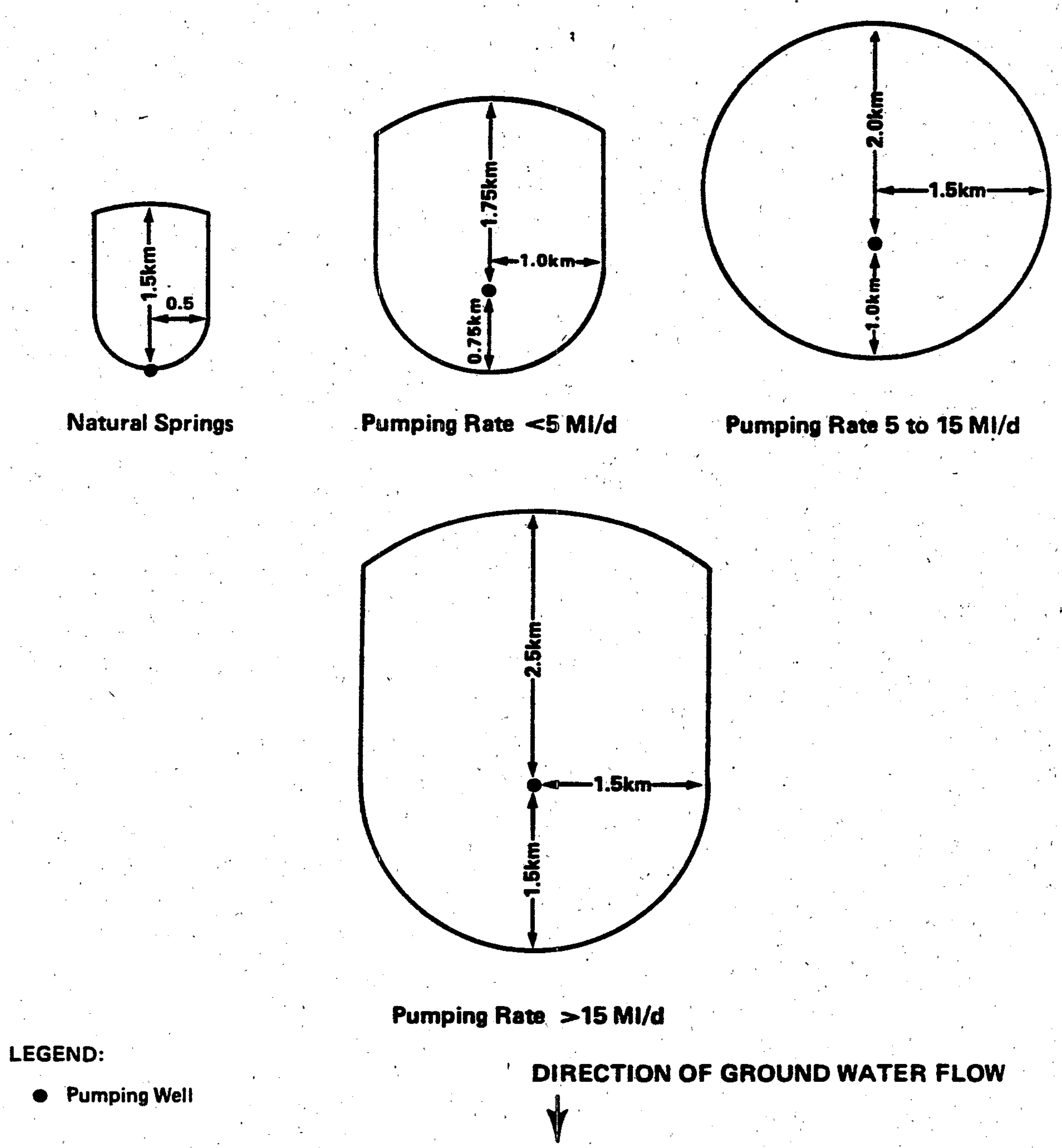
$$Z = \frac{Q}{2\pi \ Kbi}$$

where

v	=	ground-water flow velocity
t_x	=	travel time from point x to pumping well
S	=	specific yield or storativity
K	=	hydraulic conductivity
b	=	saturated thickness
i	=	gradient
r_w	=	well radius
r_x	=	distance from point x to pumping well
$\pm$	=	whether point x is upgradient (+) or downgradient (-) from pumping well.

Standardized forms, such as those shown in Figure 4-6, were developed using data from approximately 75 different possible sets of hydrogeologic parameters with varying pumping rates, hydraulic gradients, storativities, and aquifer thicknesses. When a WHPA is to be delineated for each well, the standardized form that most closely matches the pumping rate and parameters at the well is used. The standardized form is drawn over the well in the appropriate direction of ground-water flow.

Figure 4-6
Examples of Standardized Forms of WHPA Delineation Using Simplified Variable Shapes (Example from Southern England for Chalk Aquifers)



SOURCE: Southern Water Authority, 1985

4.2.4 Analytical Methods

With analytical methods, WHPA's can be delineated through the use of equation(s) to define ground-water flow and contaminant transport. The uniform flow equations (Todd, 1980) shown in Figure 4-7 are often used to define the area of contribution to a pumping well in a sloping water table.

Analytical methods, such as the uniform flow equations, require the input of various hydrogeologic parameters to calculate the distance to the downgradient divide, or stagnation point, and the width of the ZOC to the well. The upgradient extent of the WHPA can then be calculated based on either a TOT or flow boundaries criterion. For example, the location of a hydrogeologic boundary such as a ground-water divide or lithologic contact, can determine the upgradient boundary of the WHPA. Site-specific hydrogeologic parameters are required as input data for each well at which the method is applied. These parameters can include the transmissivity, porosity, hydraulic gradient, hydraulic conductivity, and saturated thickness of the aquifer.

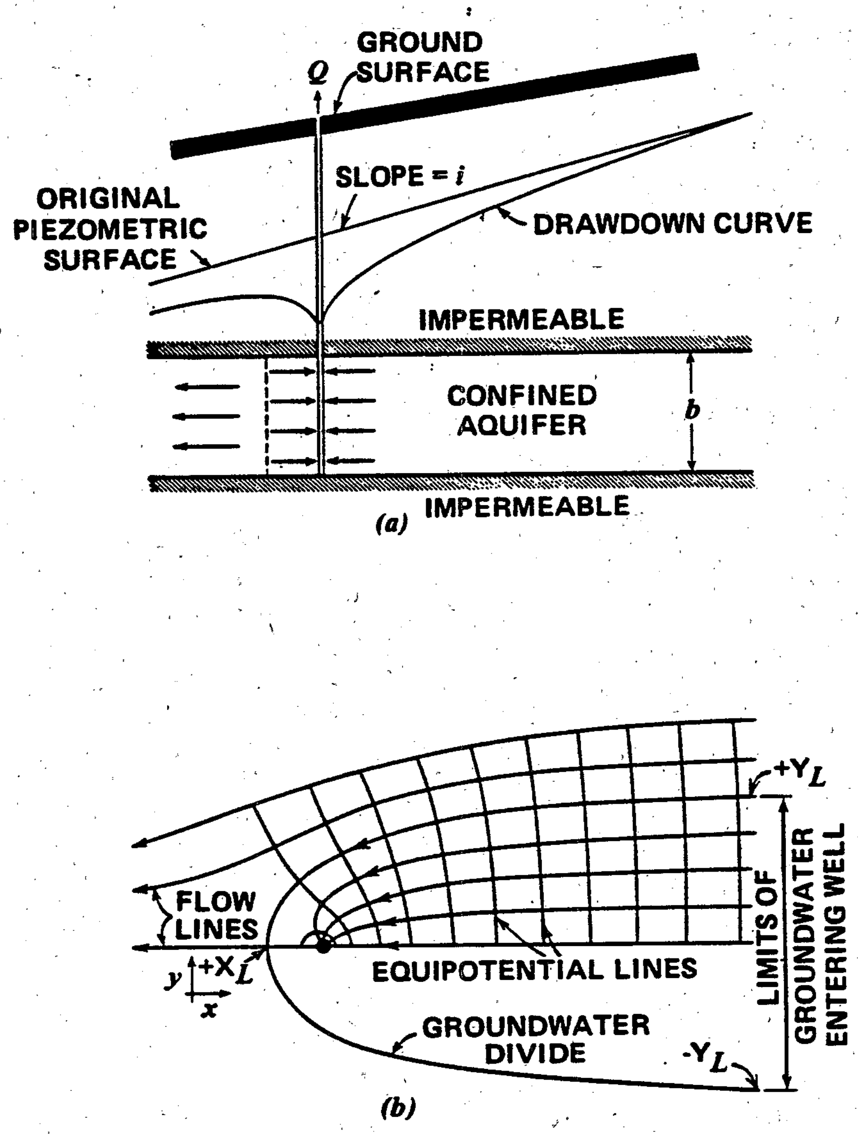
The uniform flow model can be used to calculate distances that define the ZOC of a well pumping in a sloping water table, but generally will not calculate drawdown, which determines the area of the ZOI. For flat water tables, however, analytical models can be used to calculate both the ZOC and ZOI of a well because in these cases the boundaries of the two could closely coincide (see Chapter 3). These calculations can be performed with the aid of computers. An assessment of available computer-assisted analytical flow and transport models that may be appropriate for WHPA delineation is included in van der Heijde and Beljin (1987). An excerpt from the draft of this report is included as Appendix D to this document.

Advantages. The method uses equations that are generally easily understood and solved by most hydrogeologists and civil engineers. In addition, it takes into account some site-specific hydrogeologic parameters. It is, furthermore, the most widely used method, allowing comparisons with other WHPA programs. Finally, it is considered an especially valid approach for assessing drawdown in the area closest to a pumping well.

Disadvantages. The methods use models that generally do not take into account hydrologic boundaries (e.g., streams, canals, lakes, etc.), aquifer heterogeneities, and non-uniform rainfall or evapotranspiration.

Costs. Costs of using analytical methods to delineate WHPA's are relatively low, although implementation costs can be high if site-specific hydrogeologic data must be developed

Figure 4-7
WHPA Delineation Using the Uniform Flow Analytical Model



$$\underbrace{-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q} Y\right)}$$
UNIFORM-FLOW EQUATION

$$\underbrace{X_L = -\frac{Q}{2\pi Kbi}}$$
DISTANCE TO DOWN-GRADIENT NULL POINT

$$\underbrace{Y_L = \pm\frac{Q}{2Kbi}}$$
BOUNDARY LIMIT

LEGEND:

● Pumping Well

Where:
Q = Well Pumping Rate
K = Hydraulic Conductivity
b = Saturated Thickness
i = Hydraulic Gradient
π = 3.1416

SOURCE: Todd, 1980

NOT TO SCALE

for each WHPA. The data may be derived from pertinent local or regional hydrogeologic reports. If reports are not available or more accuracy is desired, data collection may involve site studies, including test hole drilling and pump tests.

Example 1: Massachusetts. A town in Massachusetts has applied an analytical method to define a WHPA. The distance to the downgradient stagnation point and the envelope of the area of contribution were calculated using the uniform flow equations, as shown in Figure 4-8 (Anderson-Nichols & Co., 1985). The distance to the downgradient divide (X), or stagnation point at the well, was calculated using the equation

$$X = \frac{Q}{2\pi Ti} = 1{,}167 \text{ feet}$$

where

Q = pumping rate of the well = 134,760 ft^3/day

i = hydraulic gradient of the water table = 0.00125

T = aquifer transmissivity = 14,700 ft^2/day.

The maximum width of the influx zone (Y) is calculated using the equation

$$Y = \frac{Q}{Ti} = 7{,}334 \text{ feet.}$$

The distance to the upgradient limit was set as the distance to the upgradient regional ground-water divide, which in this case was equal to 3,800 ft.

Example 2: Massachusetts. Another town in Massachusetts delineates the key WHPA zone using the uniform flow model to calculate the distance to the downgradient stagnation point and the envelope of the area of contribution (Horsley and Whitten, 1986). The upgradient limit is drawn as the geologic contact between the unconsolidated aquifer and low permeability bedrock.

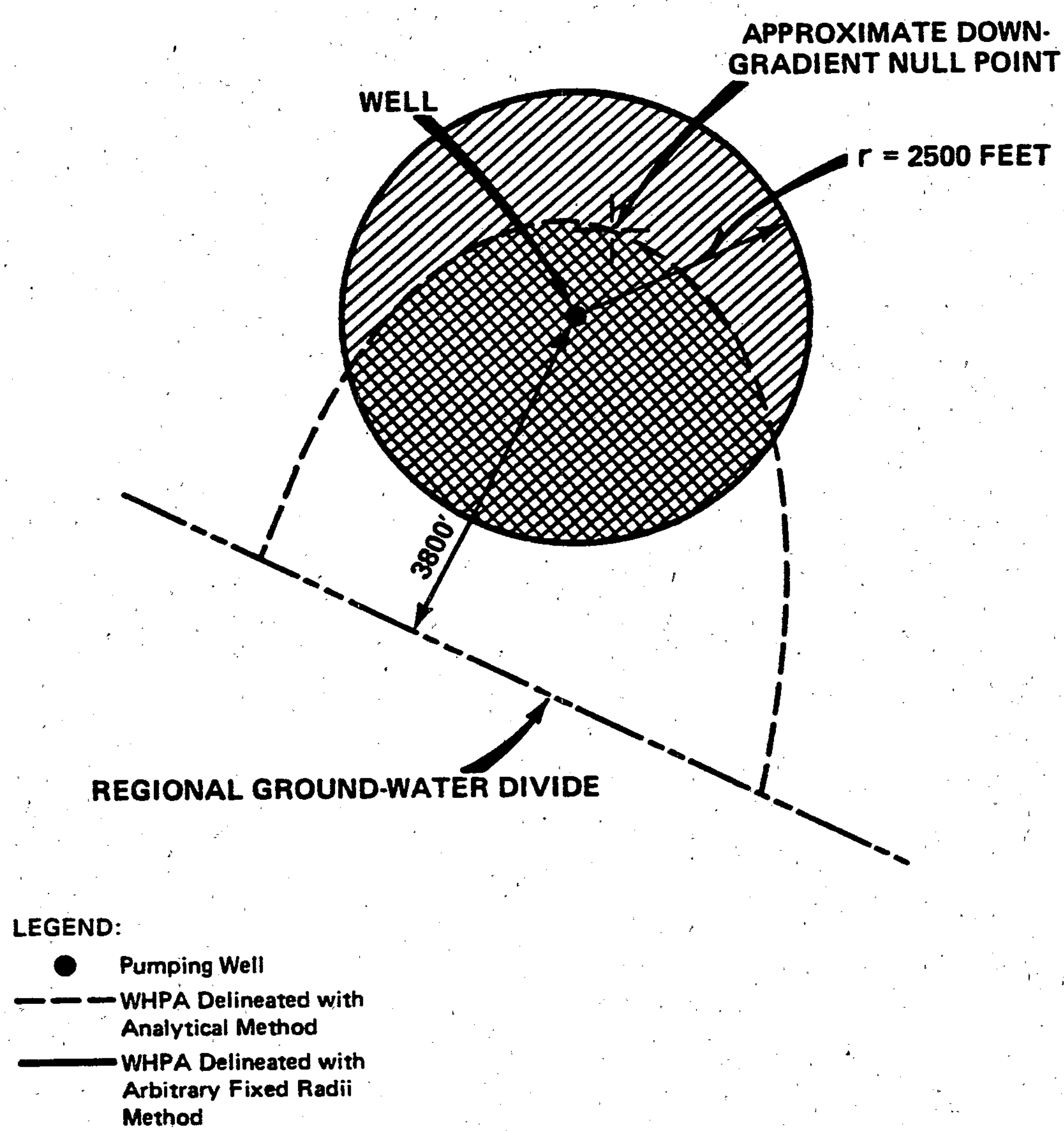
Example 3: Cape Cod. Distance-drawdown curves, analytical models, and data on local hydrogeology have been used to delineate WHPA's by the Cape Cod Planning and Economic Development Commission (Horsley, 1983). An example is shown below for a 1 MGD well; delineation is accomplished in a three-step process.

Step 1 involves identifying the distance to the downgradient drainage divide from a well by a graphical technique that involves the use of distance-drawdown curves (Figure 4-9). Three plots are shown in Figure 4-9. Plot A represents the sloping water levels near the well prior to the start of pumping. Plot B represents the cone of depression (drawdown) created around the pumping well. These two plots are used to construct Plot C by substracting the drawdowns from the sloping water levels. The distance to the downgradient divide is then determined from the shape of Plot C, the adjusted cone of influence, to be about 850 feet.

Step 2 involves identifying the distance criterion threshold to the upgradient drainage divide. The basis for this step is the Strahler prism model for ground-water flow on Cape Cod (Strahler, 1966). In this step, the well is assumed to be drawing water from the top 75 feet of the aquifer, which is 225 feet thick. Because the ratio of the well depth to aquifer thickness is 1:3, the distance to the upgradient null point is assumed to

Figure 4-8

WHPA Delineation Using Arbitrary Fixed Radii, Analytical Model, and Hydrogeologic Mapping (Example from Massachusetts)

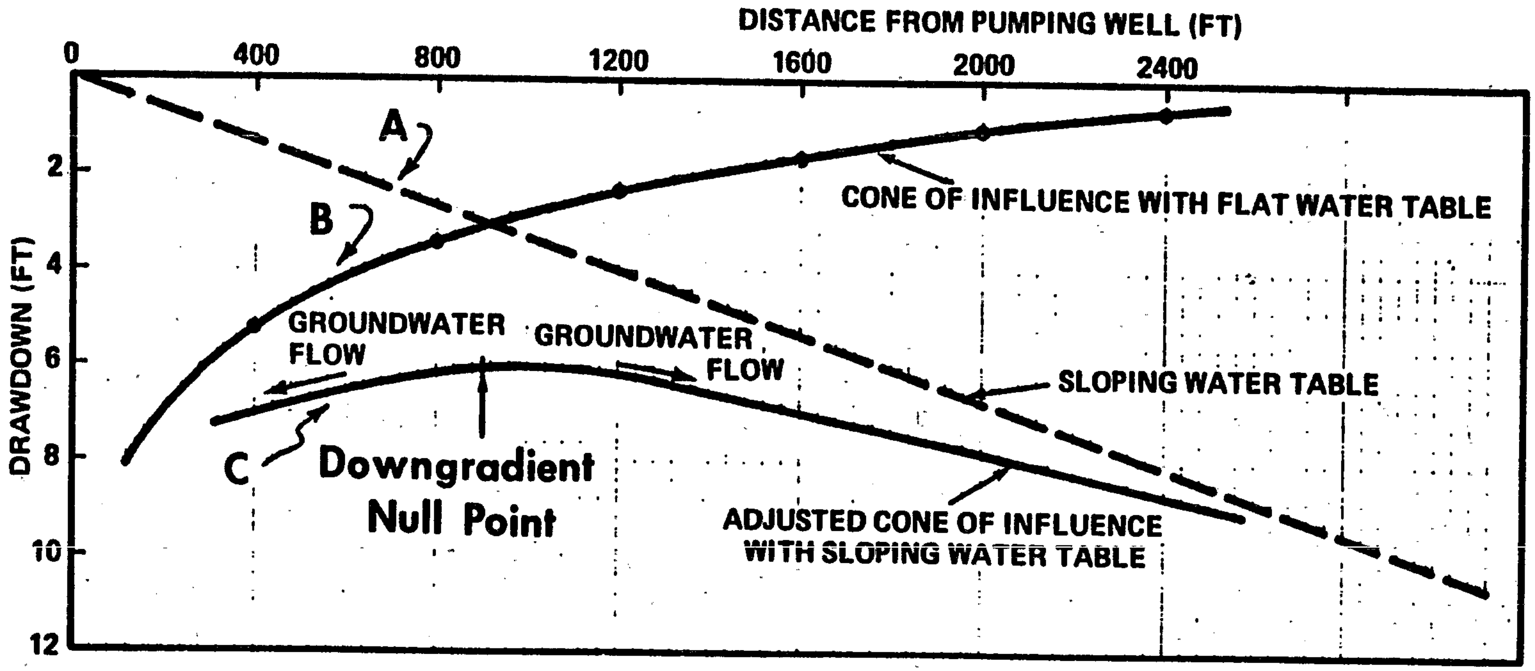


SOURCE: Anderson-Nichols & Co., 1985

NOT TO SCALE

Figure 4-9

WHPA Delineation Using Analytical Models
Step 1: Determination of Downgradient Null Point Using Pumping Test Data
(Example from Cape Cod, Massachusetts)



SOURCE: Horsley, 1983

equal one-third the distance to the regional ground water divide, which is 10,500 feet in the example (Figure 4-10).

Step 3 consists of outlining the WHPA. This is done by determining the area required to supply ground water to a well based on the annual average ground-water recharge rate. Once the area is determined, it is drawn on a map using a planimeter and the downgradient and upgradient divides as guidelines. The final WHPA delineation for the well is shown in Figure 4-11. For this well, the area of the WHPA was calculated by dividing the well pumping rate (1 million gallons per day) by the ground-water recharge rate (13 inches per year), and the area of the WHPA was determined to be 45,046,500 ft^2.

4.2.5 Hydrogeologic Mapping

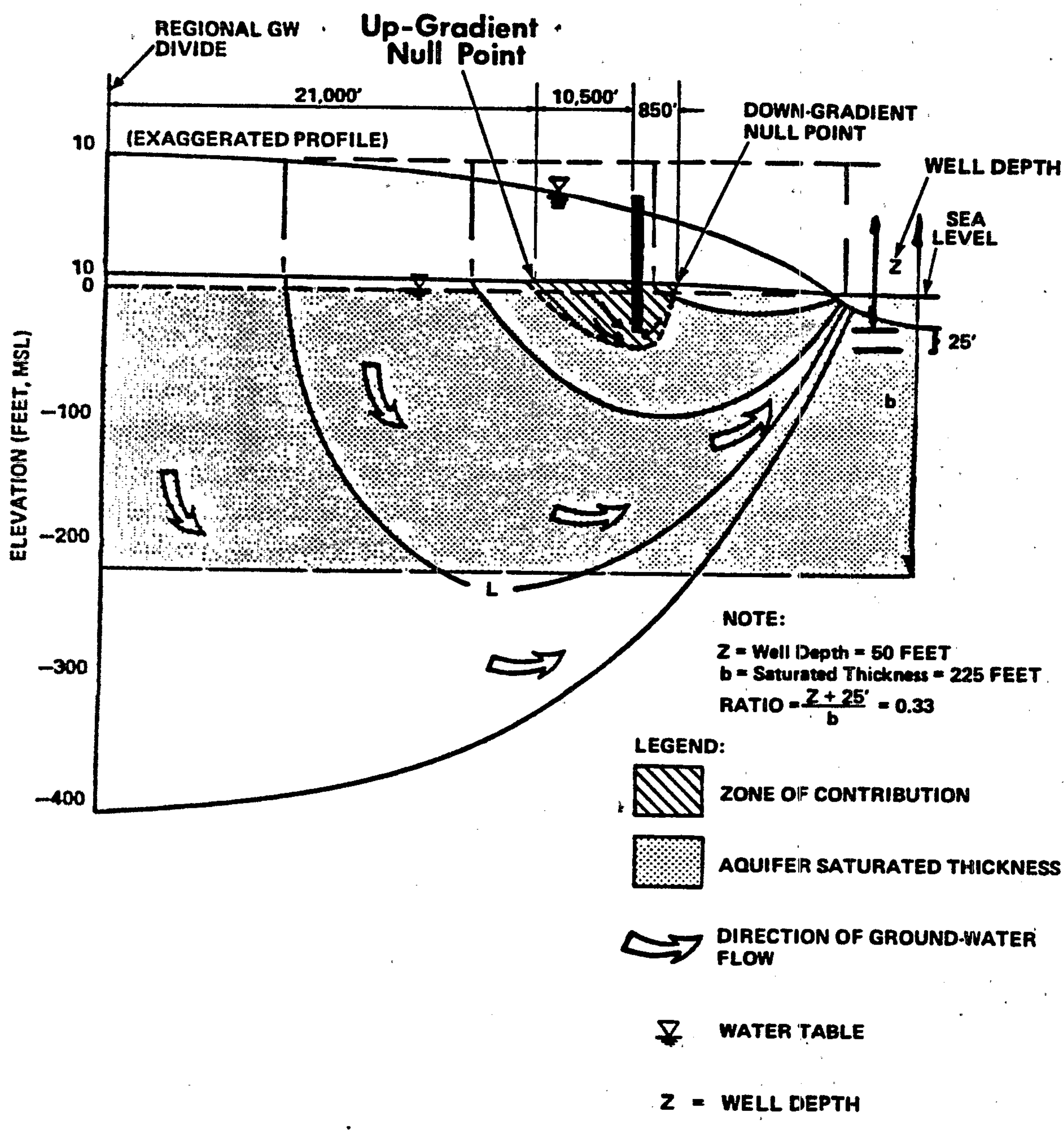
In many hydrogeologic settings, flow boundary and TOT criteria can be mapped by geological, geophysical, and dye tracing methods. The flow boundaries are defined by lithologic variation or permeability contrasts within the aquifer. Geological observations may provide surface indications of lithology changes, which will correlate with WHPA boundaries (Figure 4-12). Surface geophysical data can be used to map the spatial extent or thickness of unconfined aquifers. Hydrogeologic mapping may also include mapping of ground-water levels in order to identify ground-water drainage divides, as shown in Figure 4-13.

Delineation of upland carbonate aquifers having rapid recharge into conduit karst during storm events can be done initially by topographic analysis of drainage basin divides, supplemented by mapping the water table using water levels in wells and springs. Subsequent refinement of conduit recharge patterns is possible by using dye tracing techniques, especially during high-flow conditions. Under such conditions, sub-basins can become integrated or even spill over into other basins, reflecting the complex nature of karst systems. Although less frequently reported in scientific literature, these methods can also be used to delineate recharge and flow systems in non-carbonate fractured bedrock aquifers.

Advantages. Hydrogeologic mapping is well suited to hydrogeologic settings dominated by near-surface flow boundaries, as are found in many glacial and alluvial aquifers with high flow velocities, and to highly anisotropic aquifers, such as fractured bedrock and conduit-flow karst.

Disadvantages. The method requires specialized expertise in geologic and geomorphic mapping, plus significant judgment on what constitute likely flow boundaries. This method is also less suited to delineating WHPA's in large or deep aquifers.

Figure 4-10
WHPA Delineation Using Analytical Models
Step 2: Identify Upgradient Null Point Based on Strahler Prism Model (Example from Cape Cod, Massachusetts)



SOURCE: Horsley, 1983

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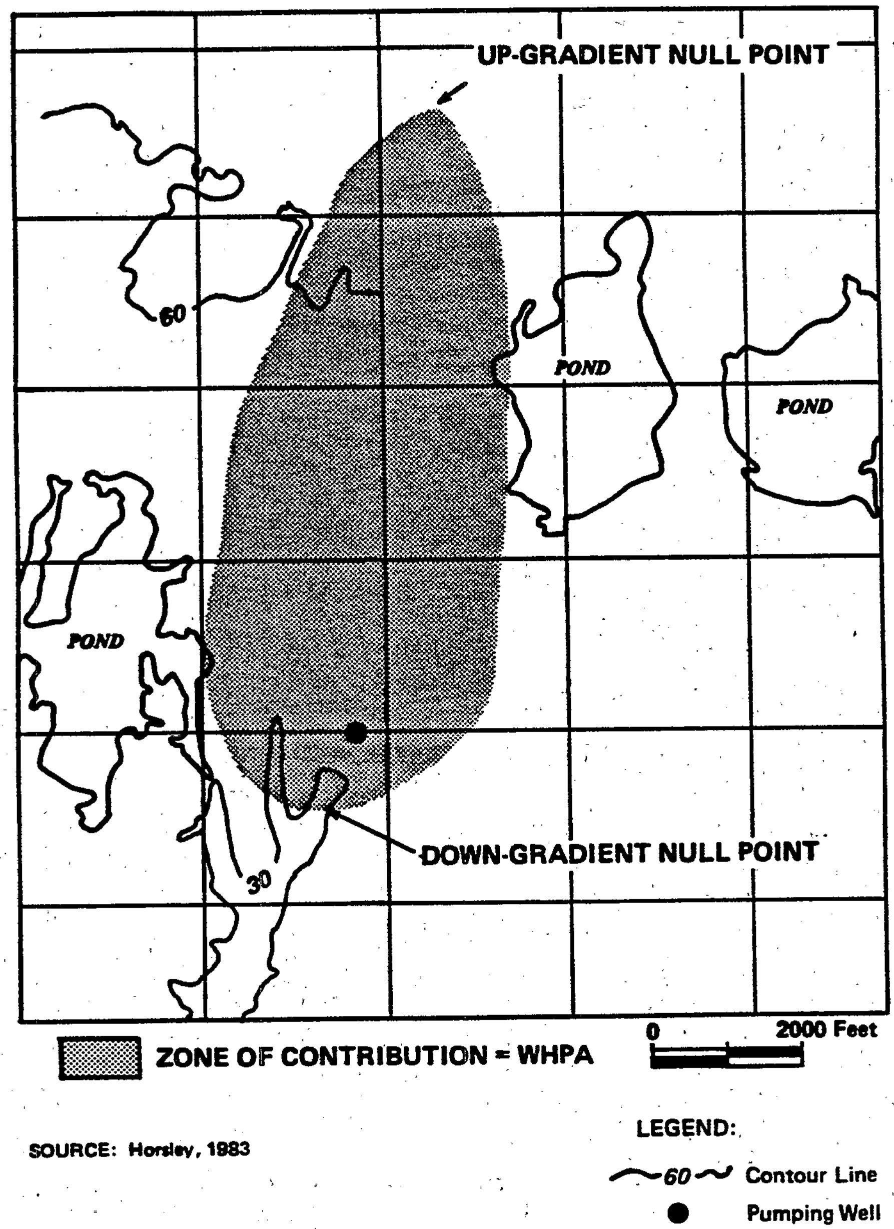
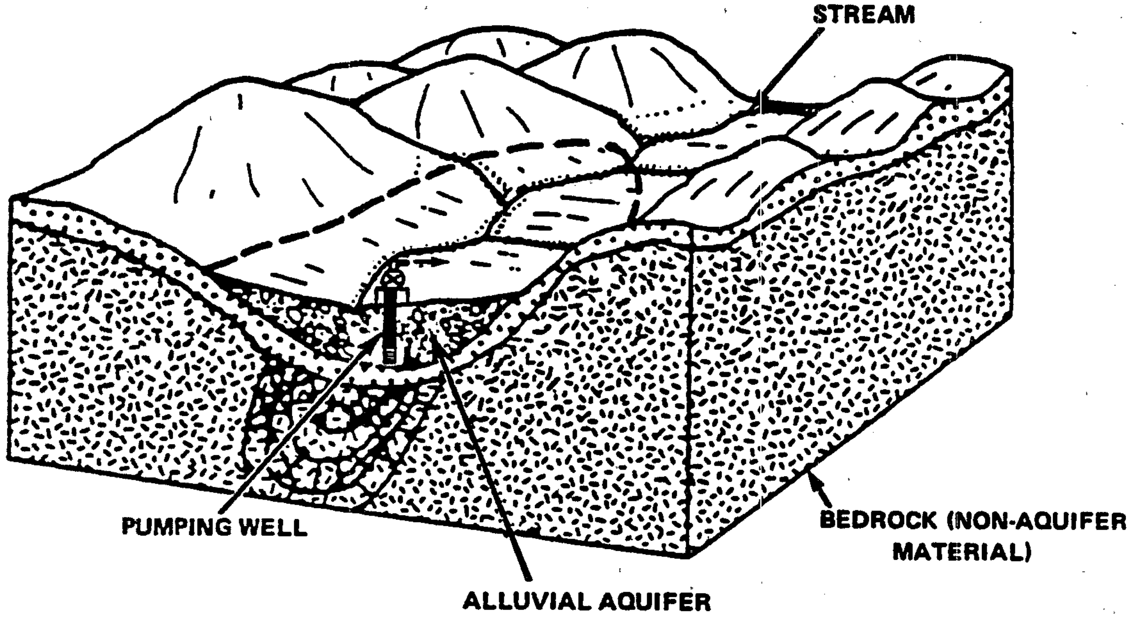
Figure 4-11
WHPA Delineation Using Analytical Models
Step 3: WHPA Delineation Using Upgradient and Downgradient Null Point
(Example from Cape Cod, Massachusetts)



SOURCE: Horsley, 1983

Figure 4-12
WHPA Delineation Using Hydrogeologic Mapping (Use of Geologic Contacts)

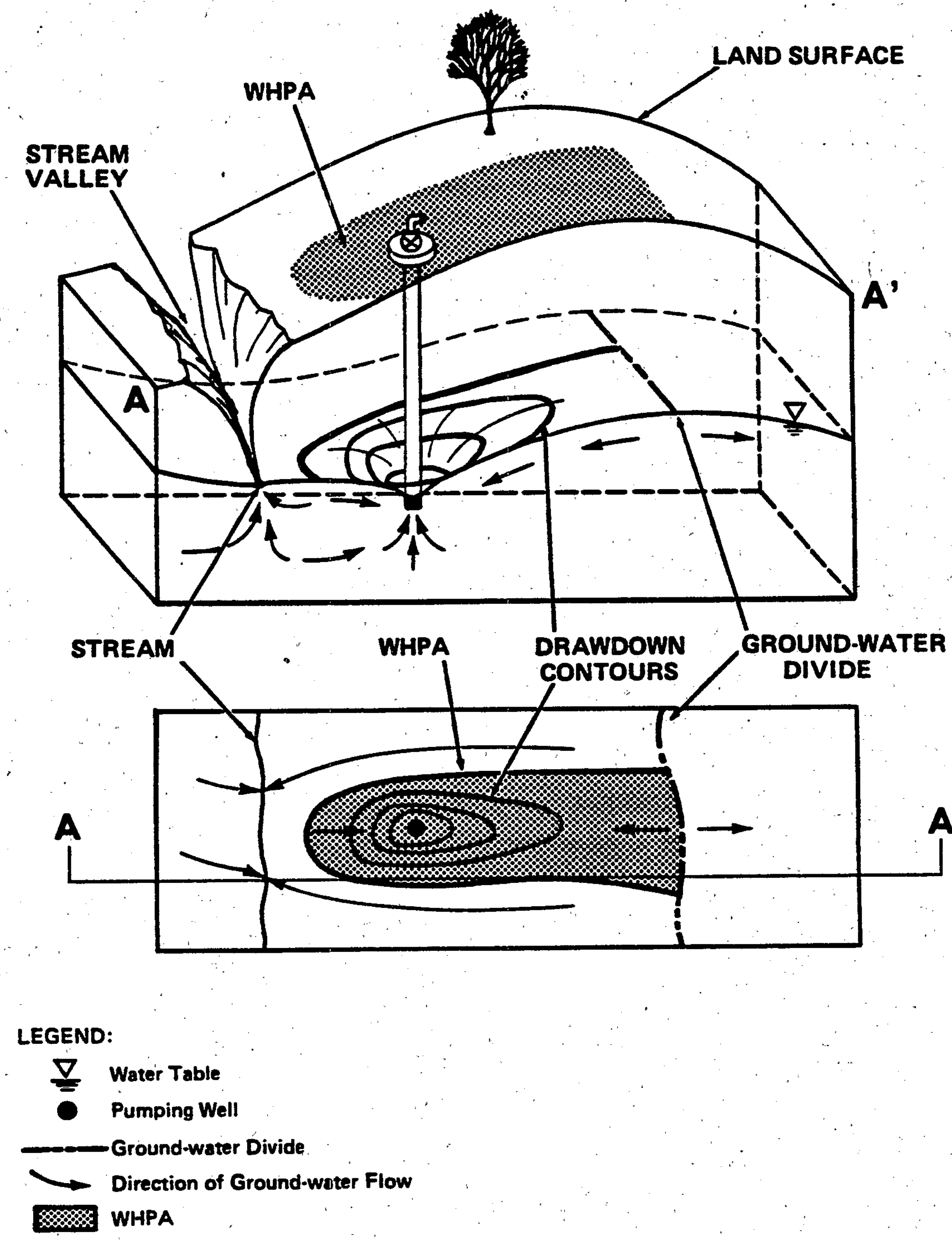


▬ ▬ ▬ Primary WHPA Boundary Drawn as Contact Between Aquifer and Non-Aquifer Material

NOTE: A secondary protection zone could be delineated based on the larger area of recharge derived from surface runoff, and inferred from topography and basin boundaries.

NOT TO SCALE

Figure 4-13
WHPA Delineation Using Hydrogeologic Mapping (Use of Ground-water Divides)



Costs. Costs of developing and implementing a wellhead protection program using hydrogeologic mapping are variable. Costs may be relatively low if considerable data are already available or if the general hydrogeology of the ground-water system is known. The particular type of hydrogeologic mapping technique used will also determine costs. In general, geophysical techniques are the most costly, followed by mapping of geologic contacts, dye tracing, regional water level mapping, and basin delineation using topographic mapping. Costs may be high if little hydrogeologic information is available in an area and if test holes and/or pump tests are necessary to confirm the mapping.

Example: Vermont. Vermont utilizes a method in which mapping of geologic contacts is combined with simplified fixed-ring calculations (subsection 4.2.2) (Vermont Department Water Resources, 1985). In an example from Vermont (shown in Figure 4-14), a primary protection area is delineated using hydrogeologic calculations while a secondary area is delineated with hydrogeologic mapping of the well's recharge area. Hydrogeologic mapping in this case is based on physical boundaries and the prevailing topography, with the assumption that shallow local ground-water flow mirrors topography.

Hydrogeologic mapping has also been used to delineate parts of WHPA's in a town in Massachusetts, where the upgradient extent of the WHPA is formed by the regional ground-water divide, as shown in Figure 4-8.

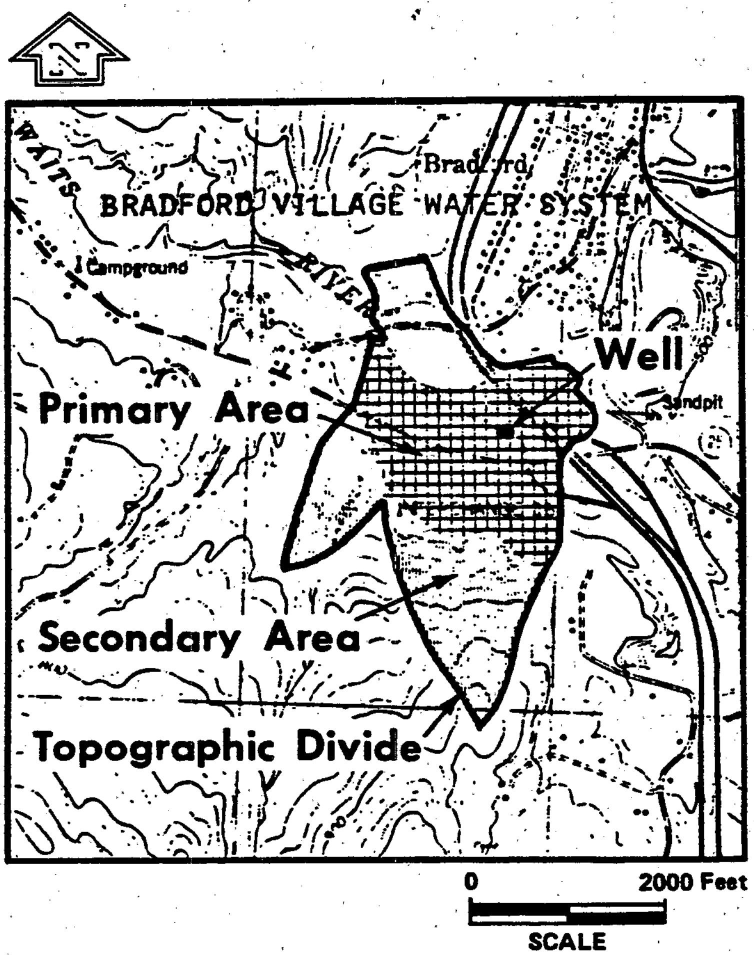
Other Hydrogeologic Mapping Tools

Tracer Tests. Tracing techniques can be used to map underground conduits by injecting dyes or tracers into a ground-water system. The dye is introduced into a sinkhole or stream that flows into ground water suspected to flow to the supply source for which the WHPA is being delineated. Water from the supply well or stream is then monitored and/or observed for a period of time that is adequate for the tracer to reach the supply. If the tracer is detected in the supply, the source from which the tracer was injected becomes part of the WHPA. Existing contaminants in ground water can also be used as tracers to delineate flow to water supply wells. If the source of contaminants to a well is known, the information can be used to better understand ground-water flow in the area, and the specific sources of water in the well.

Example: Kentucky. Dye tracing has been used to delineate ZOC's to water supply springs in Kentucky (Quinlan and Ewers, 1985). In the example shown (Figure 4-15), the ZOC to a spring supplying a town differs from a ZOC that would be interpreted from observing topography and mapping potentiometric surfaces. In this example, although the spring was hydraulically downgradient from a contaminated pond, dye tracing revealed that the spring would not be affected.

Geophysics. Surface geophysical techniques have also been applied in aquifer mapping investigations. These techniques measure the surface response of subsurface elastic,

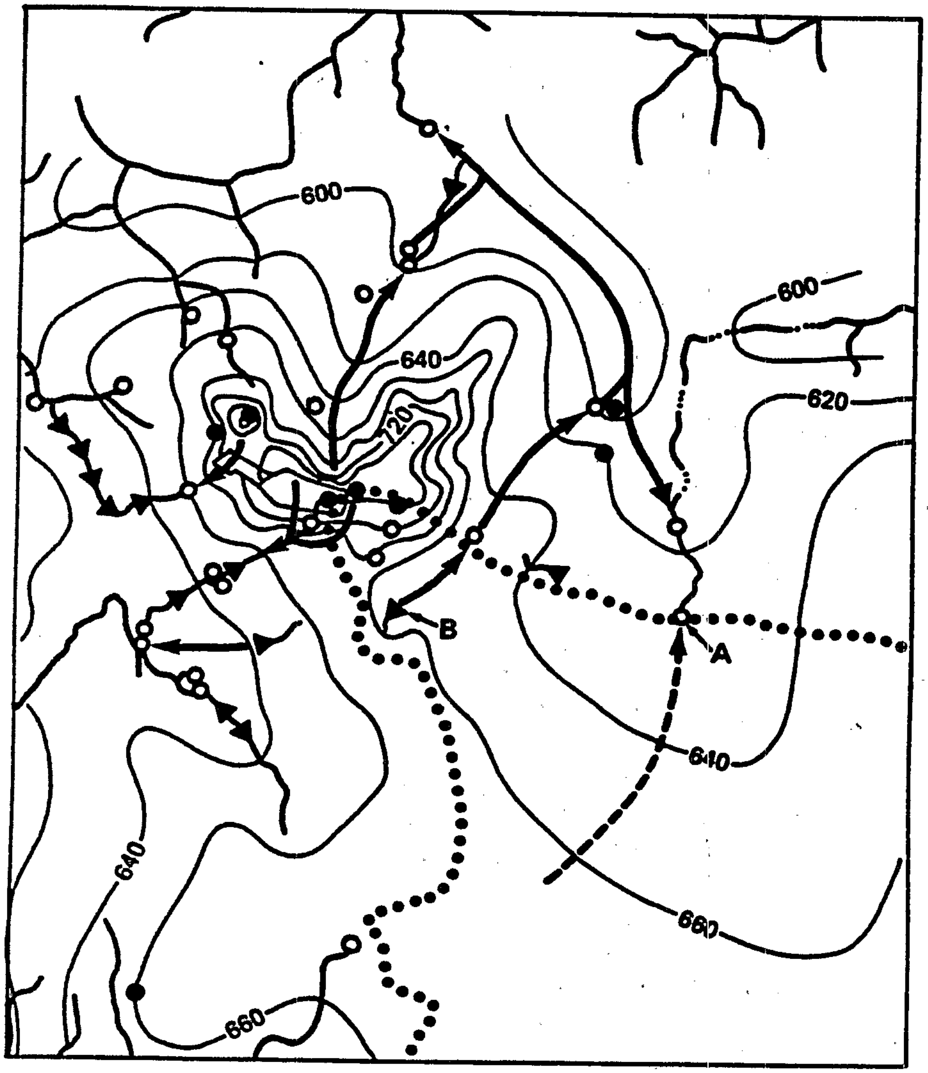
Figure 4-14
WHPA Delineation Using Hydrogeologic Mapping (Example from Vermont)



PRIMARY AREA (STRATIFIED DRIFT)
SECONDARY AREA (TILL AND BEDROCK)

SOURCE: Vermont Dept. of Water Resources, 1985

Figure 4-15
WHPA Delineation Using Hydrogeologic Mapping: Dye Tracing (Example From Kentucky)



-600- Potentiometric surface
Traced flow route
Sinking spring
Spring-fed stream
Intermittent stream
Sinking stream
Inferred ZOC of spring A based on mapping of potentiometric surface
A Municipal water supply spring
Inferred direction of ground-water flow

Sinking stream B was found to not be in ZOC of spring A, although this would be inferred from potentiometric surface.

Modified from Quinlan and Ewers, 1985

NOT TO SCALE

density, electrical, or magnetic contrasts. The resulting subsurface interpretations can provide information on the lithologic and hydrologic characteristics of unconfined aquifer systems.

The nature of the hydrogeologic setting determines the applicability of a particular geophysical method. In many ground-water studies, several different geophysical methods are applied to the same survey area. In general, the selection of a geophysical technique depends on: the physical nature of the survey area, the desired depth of penetration, the data resolution requirements, and the available resources.

Geophysical methods model the subsurface environment according to simplifying assumptions. Subsurface interpretations are generally improved when information from test borings or observation wells are available to constrain the data sets. One common strategy is to use surface geophysical data to correlate between boreholes or to extrapolate borehole information into new terrain. In these surveys, surface geophysics functions as a rapid, inexpensive alternative to test drilling.

WHPA delineation programs can use surface geophysics to map the subsurface boundaries in unconfined aquifer systems. In these boundary delineation studies, seismic refraction and electrical resistivity techniques have been applied most consistently, with gravity and magnetic methods having only secondary applications. However, recent technological advances have resulted in the development of new techniques that have ground-water applications. Table 4-2 summarizes some of the technical characteristics, applications, advantages, and limitations of the geophysical techniques that have been used in ground-water investigations, based on a report by the Office of Ground-Water Protection (1987).

Age Assessment (Tritium). An indication of recent leakage or paths of rapid recharge into a confined aquifer is the presence of tritium in concentrations greater than atmospheric background, a consequence of the presence of post-1954 tritium from atmospheric testing of nuclear weapons. In precipitation, tritium from cosmic ray bombardment of the upper atmosphere has a quite low concentration and is variable with latitude, season, and local meteorological parameters. Thus ground water from atmospheric precipitation prior to 1952 has quite low concentrations relative to the enhanced levels subsequent to 1954.

The presence of tritium in ground water at higher concentrations (unless it results from radioactive waste disposal) can be used to determine roughly ground-water age and origin. In confined aquifers, for example, the existence of leaks in pathways could be

TABLE 4-2

Geophysical Techniques

Technique	Parameter Response	Measurements	Resolution	Penetration Depth	Applications	Advantages	Limitations
Seismic refraction	Acoustic velocity	Stations with ground contact	Good vertical description of three or four layers	Depth is equipment dependent; decreased accuracy below 100 ft	Depth to water table in unconfined aquifers; saturated thickness of aquifer; depth to bedrock in alluvial valleys; stratigraphic mapping	Quantitative results; refined acquisition and interpretation procedures	Some areas require explosives or long geophone spread lengths; noise can impair results; velocity required to increase with depth; depth limitations
Seismic reflection	Acoustic velocity	Stations with ground contact	Excellent vertical resolution	Depth is equipment dependent; limited accuracy above 100 ft; probes to 1,000 ft	Mapping of bedrock in valley fill aquifers; detailed stratigraphic mapping of sedimentary units	Velocity not required to increase with depth; moderate geophone spreads; high resolution in areas of high water table	Complex field and interpretation procedures; may require explosives; data recorded digitally; data impaired by noise; poor resolution for shallow reflections, especially for low water table
Electrical resistivity	Electrical resistivity	Station measurements with ground contact	Good vertical resolution of three to four layers	Depth is equipment dependent; limited accuracy below 400 ft	Depth to water table and salt-fresh water interface; delineation of clay layers or fine and coarse sediments; mapping unconfined aquifer boundaries	Provides some lithologic information; interpretation is quantitative; acquisition and processing procedures are refined	Limited resolution; non-uniqueness of solutions; requires large surface area for deep soundings; acquisition is slow and data impaired by noise
Electromagnetic induction	Electrical conductivity	Continuous and station measurements; no ground contact	Excellent lateral resolution; good vertical resolution of two layers	Depth is determined by the coil spacing; common depths are from 1 to 200 ft	Same as electrical resistivity	Rapid and simple data acquisition—no ground contact; good resolution	Data impaired by noise; depth limitations; interpretation is qualitative; can define only two or one layer(s) limited to simple stratigraphy
Very low frequency resistivity	Electrical resistivity	Continuous measurements with no ground contact	Same as Electromagnetic Induction (EMI)	Depth is determined by the resistivity of the terrain; performs like EMI	Same as electrical resistivity	Rapid and simple data collection; good resolution	Depth limitation; qualitative interpretation; VLF signal is intermittent; limited to simple stratigraphy
Ground penetrating radar	Dielectric constant	Continuous measurements with ground contact not necessary	Excellent vertical and lateral resolution	Depth limited by conductivity of terrain; probes from 1 to 120 ft	Map water table and shallow stratigraphy in unconfined aquifer systems	Rapid and simple data acquisition; excellent resolution	Depth of penetration severely limited in conductive terrains; complex to operate
Gravimetry	Density	Stations	Poor	Not relevant	Map bedrock and thickness of alluvial sediments	Economical and unaffected by cultural noise	Poor resolution; care required in performing measurements; data impaired by vibrational noise; interpretational ambiguities
Magnetometry	Magnetic susceptibility	Continuous airborne or land-based; land-based station measurements	Poor	Not relevant	Map sedimentary units that contain magnetic materials; map fractures and fault zones; depth of alluvium when bedrock has a measurable magnetic susceptibility	Economical	Poor resolution; limited to crystalline bedrock; interpretational ambiguities

SOURCE: Office of Ground-Water Protection (1987) determined and the extent of WHPA's could thus be modified according to the locations of such pathways. Ground water is frequently a mixture of waters of different ages and sources, which can complicate age-determination of the major portion of recharge. Because leakage into a confined aquifer can short-circuit into ground water from other recharge paths, water having a much greater isotopic age (as can be measured by carbon 14 dating) may be present also.

Trichlorofluoromethane (CCl_3F) is of anthropogenic origin and has been in the atmosphere for about fifty years. It is an additional possible tracer of leakage into confined aquifers (Thompson and Hayes, 1979), although it does not have well-defined chemical and physical behavior during ground water flow as does tritium. CCl_3F is subject to adsorption and desorption phenomena that affect its concentrations in ground water (Russell and Thompson, 1983).

It appears that detection of significant tritum concentrations in confined aquifers may be one of the most expedient initial methods of evaluating the leakiness of confining strata in the short term. It must be kept in mind that mere leakiness of an aquifer is not equivalent to finding contamination by a pollutant, merely an indication of the existence of a possible pathway should a contaminant subsequently be introduced to that part of the flow system.

4.2.6 Numerical Flow/Transport Models

WHPA's can be delineated using computer models that approximate ground-water flow and/or solute transport equations numerically. A wide variety of numerical models is presently available both commercially and through organizations such as the U.S. Geological Survey (USGS), Holcomb Institute's International Ground-Water Modeling Center (IGWMC), and the National Water Well Association (NWWA).

Numerical flow/transport models are particularly useful for delineating WHPA's where boundary and hydrogeologic conditions are complex. Input data may include such hydrogeologic parameters such as permeability, porosity, specific yield, saturated thickness, recharge rates, aquifer geometries, and the locations of hydrologic boundaries. Solute transport parameters such as dispersivity may also be incorporated in these models.

Depending upon the size of the area to be modeled and the number of cells or elements, these models can be run on a mainframe or microcomputer. Intermediate-type models that use combinations of analytical methods to generate head field distributions and numerical methods to generate particle tracing maps are also available. Such models may not account for all boundary conditions at a site, however.

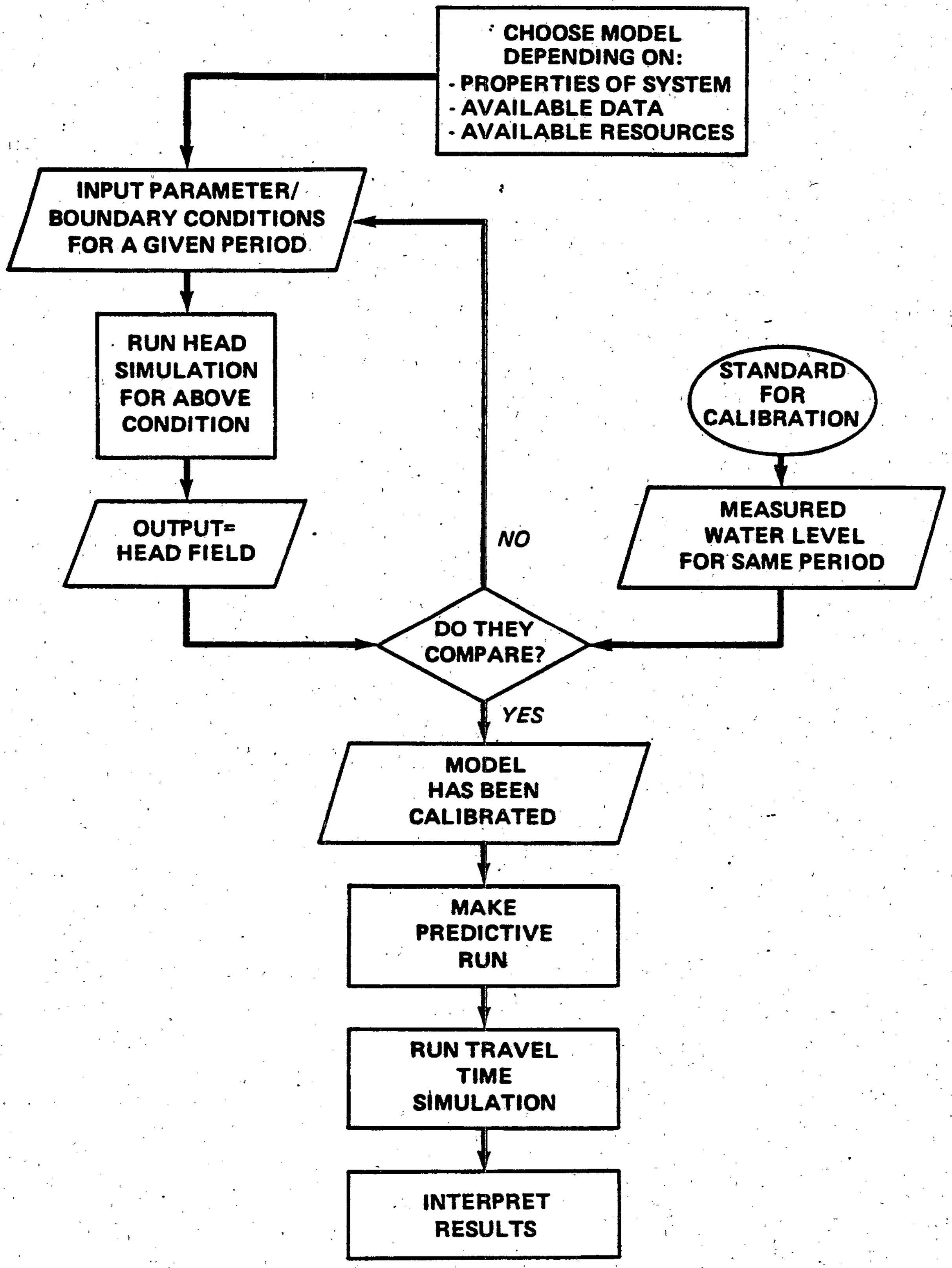
Criteria such as drawdown, flow boundaries, and TOT may be mapped using numerical methods, typically in a two-step procedure. First, a hydraulic head field distribution is generated with a numerical flow model under a prescribed set of hydrogeologic parameters and conditions, and with a selected flow boundaries criterion to determine the extent of the modeling domain. Second, a numerical solute transport model that uses the generated head field as input calculates the WHPA based on the preselected criterion. Figure 4-16 illustrates a flow chart of some typical components of this procedure. Some information from a draft report on available numerical models that may be appropriate for WHPA delineation is included as Appendix D to this report (van der Heijde and Beljin, 1987). An additional, useful guide for model selection is provided in a report by the EPA Office of Research and Development (1987).

Advantages. This method provides a very high potential degree of accuracy and can be applied to nearly all types of hydrogeologic settings. The models can also be used to predict the dynamic aspects of the WHPA such as changes in the size of the WHPA resulting from natural or man-caused effects. Specific advantages and disadvantages associated with individual models are reviewed in the report "Model Assessment for WHPA Delineation" by IGWMC (Beljin and van der Heijde, 1987).

Disadvantages. Costs for this method are usually relatively higher than others. Considerable technical expertise in hydrogeology and modeling is required to use this method. However, the cost may be warranted in areas where a high degree of accuracy is desired. Due to limitations on model grid spacing and density, numerical models are less suitable than analytical methods in assessing drawdowns close to pumping wells. For this reason, WHPA delineation in The Netherlands in recent years has focused on combining analytical methods for the near-field and numerical models for the bulk of the protection area.

Costs. Costs of developing and implementing a numerical model to delineate WHPA's can be relatively high, depending upon the availability and quality of data, the number of wells, and the complexity of the hydrogeology. However, if adequate data bases exist and the hydrogeology of the area is known, numerical models can be cost effective. Numerical modeling can also be less expensive if relatively homogeneous hydrogeologic conditions exist and extensive data input is not necessary. In this case, a large number of "default values" for some of the hydrogeologic parameters can be used, while using better-known values for the more sensitive parameters.

Figure 4-16
Simulation Procedure Used in WHPA Delineation with Numerical Modeling



Example: **Florida.** The Counties of Broward, Dade, and Palm Beach in Florida use numerical ground-water models to delineate WHPA's. Figure 4-17 shows a map with the numerically generated 30-day, 210-day, and 500-day TOT's (based on the multiple WHPA zone approach) for a well field in the Biscayne aquifer.

4.3 WHPA DELINEATION METHOD COSTS

Estimates of potential costs for each of the six WHPA delineation methods are shown in Table 4-3. These are rough estimates on a per-well basis, considering labor costs and level of expertise required for each method. The table also includes potential overhead costs that may be encountered with each method, although dollar figures have not been assigned to overhead. Labor costs for the various levels of expertise are based on a survey by the National Water Well Association on salaries of ground-water scientists in the United States (NWWA, 1985). The costs are expressed in uninflated dollars.

Several assumptions built into the figures in Table 4-3 include:

- WHPA's will be delineated by personnel and staff at the agency in charge of the WHPA program, possibly aided by consulting firms.
- Each method requires a different level of technical expertise to apply.
- Data on hydrogeology of the areas in which WHPA's are being delineated are relatively available, although some data collection and searching may be required.

Manhour requirements for each method have been projected in ranges of hours. The higher end of the range may apply if a relatively large amount of data collection is required or the data are not readily available. It may also apply if the personnel are unfamiliar with WHPA delineation methods and/or have not reached a level on the "learning curve" where WHPA's can be delineated efficiently. The lower end of the range of manhours may apply if data are generally easily available and/or the personnel doing the delineation are familiar with and have used the delineation methods. For estimates in Table 4-3, it was assumed that the average annual salary estimated from that survey was roughly equivalent to that of a mid-level hydrogeologist. Salaries of other levels were then estimated from that figure.

Potential overhead costs include those for equipment to collect hydrogeologic data, computer hardware and software, and the costs associated with report preparation, including typing and creating maps and figures. In general, if many of these items are already available to the agency or organization doing the delineation, potential overhead

Figure 4-17
Numerical Model Application to Biscayne Aquifer Well Field

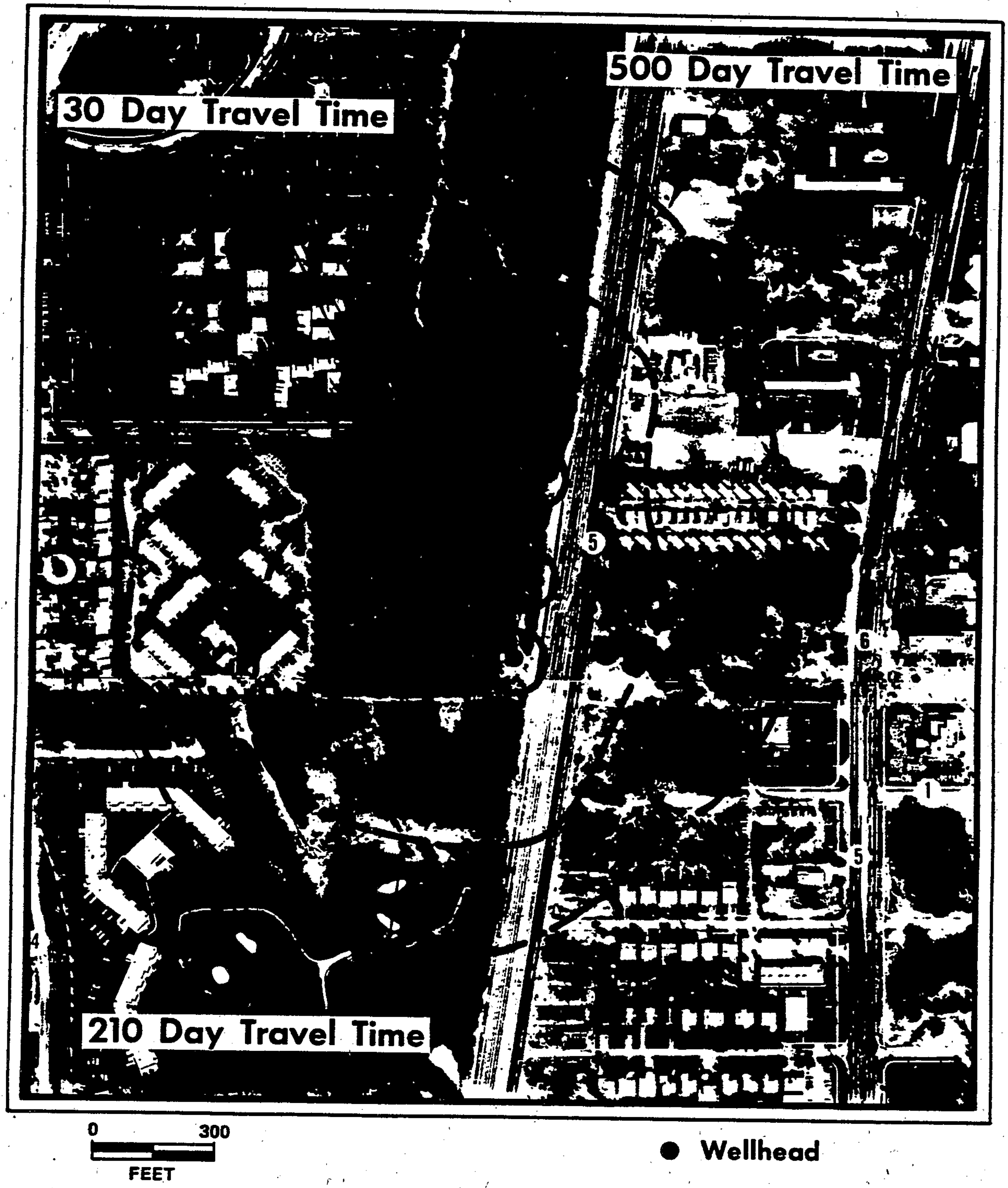


TABLE 4-3

Costs of Delineation Associated with Various WHPA Methods

Method	Manhours Required per well	Level of Expertise*	Cost per Well	Potential Overhead Costs
Arbitrary Fixed Radii	1-5	1	$10-50	L
Calculated Fixed Radii	1-10	2	$13-125	L
Simplified Variable Shapes	1-10	2	$13-125	L-M
Analytical Methods	2-20	3	$30-300	M
Hydrogeologic Mapping	4-40	3	$60-600	M-H
Numerical Modeling	10-200+	4	$175-3500+	H

*Hourly wages per level of expertise assumed to be (based on NWWA, 1985)

1.	Non-Technical	$10.00
2.	Junior Hydrogeologist/Geologist	$12.50
3.	Mid-Level Hydrogeologist/Modeler	$15.00
4.	Senior Hydrogeologist/Modeler	$17.50

costs become less significant. These figures do not reflect costs for consulting firms potentially engaged in this work. It should be noted that the greatest expenses are typically related to data acquisition, and these are clearly State- and WHPA-specific.

4.4 WHPA COMPARATIVE ANALYSIS

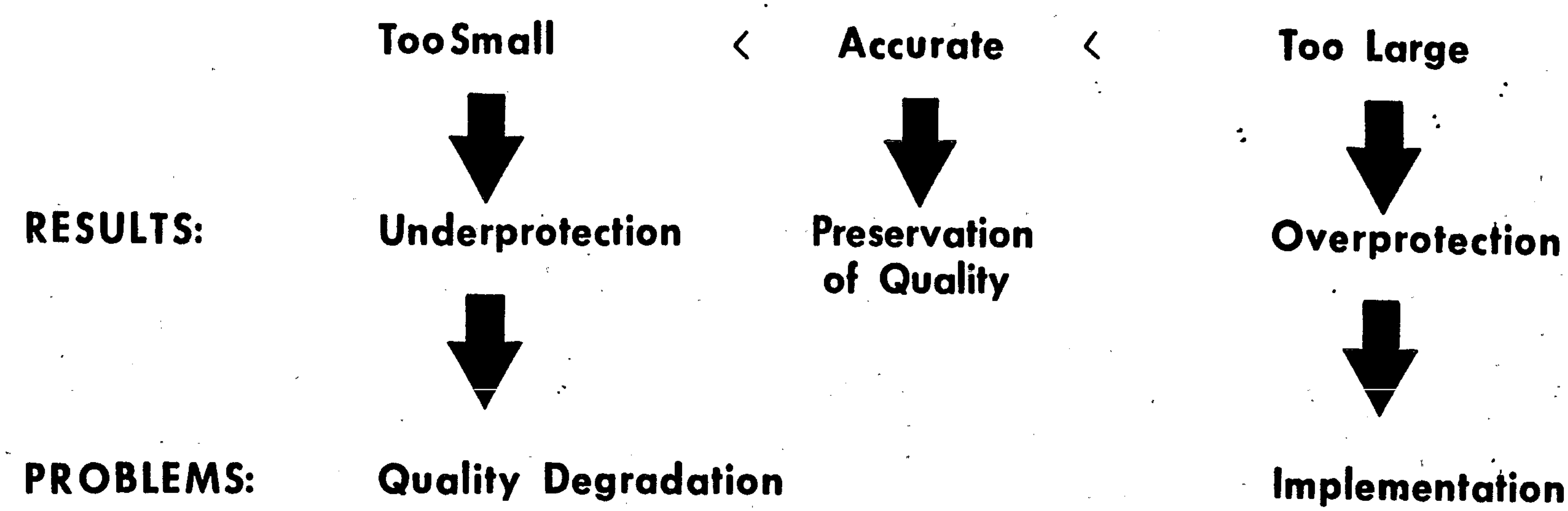
Once a desired criterion and criterion threshold have been selected, one or more WHPA delineation method(s) will be chosen to "map" the criterion. To aid in method selection, a comparative analysis of delineated areas resulting from different methods may be performed. Results of this comparison should consider relative accuracy, ease of implementation, and costs. For example, if a fixed radius method were being considered for delineating WHPA's in an entire State, a comparative analysis for a limited number of wells using more sophisticated (and presumably more accurate) methods could help determine if the simpler and less costly method provides adequate results. Examples of comparative analyses of WHPA delineations done for actual wells in several locations are described in detail in Appendix B.

Two approaches can be used in WHPA comparative analyses. One approach is to compare areas of protection that result from applying the same method of delineation to different hydrogeologic settings. A second approach is to compare areas of protection that result from applying different methods of delineation to the same hydrogeologic setting.

With any analysis, a basic assumption is made that there is one method that provides results most indicative of actual conditions. Once the various areas have been delineated in the comparative analysis, the tradeoffs of accuracy versus costs versus speed of implementation, can be more fully considered in any given State or hydrogeologic setting within a State.

Figure 4-18 conceptually illustrates the effects of accuracy on the degree of protection and ease of implementation. If the area delineated by a method is smaller than that delineated by the method assumed to be the most accurate, under-protection may occur. This may result in possible degradation of water supplies. If the area is too large relative to the accurate method, over-protection may occur and result in implementation problems. The common European "rule" for determining the extent of WHPA's is "as large as necessary, as small as possible."

Figure 4-18
WHPA Comparative Analysis
What is Accuracy?



4.5 METHOD SELECTION CONSIDERATIONS

The amount of effort required to select a method is largely reduced once the desired criterion has been selected. That is, the method selected must be suitable to map or delineate the selected criterion or criteria. For example, if the criterion selected is distance, then the only appropriate methods to map distance are arbitrary fixed radii and hydrogeologic mapping. Table 4-4 shows the suitability of each method to map each criterion. A detailed technical discussion of the approaches to selecting analytical or numerical models (either two-dimensional or three-dimensional) for a typical glacial, stratified-drft, river-valley aquifer in New England is provided by Morrissey (1987).

As in the case of criteria selection (Section 3.4), choosing a method depends on various technical and policy considerations. The choice of method is tied less to the protection goal, however, than to the accuracy of delineation desired, and the financial resources available for delineation.

4.5.1 Technical Considerations

To guide the States in the process of selecting a method, a matrix of technical evaluation factors versus methods is presented as Table 4-5. The matrix is blank to allow the States or local agencies to assign their own rankings according to site-specific conditions. An "H" (High) ranking implies that the method is relatively useful or beneficial in satisfying the technical consideration. The factors that might be used to evaluate the method are described below. Understanding the basis of the method and the input data requirements, applying the method, and evaluating the method's results are all significant considerations.

Extent of Use. It is useful to identify how commonly the method is used (e.g., whether it is presently used by regulatory agencies or is in the process of being adopted).

Simplicity of Data. The amount and types of data required for method application are quite significant. The data required may be site-specific (i.e., developed specifically for method application) or regional (i.e., approximate and already available).

Suitability for a Given Hydrogeologic Setting. An important consideration is the capability of a method to be applied to the hydrogeologic setting in the State. It may be important to evaluate how suitable the method would be to incorporate the effects of "sources" and "sinks," boundary conditions, variable aquifer parameters, and other technical factors.

Table 4-4
Relationship Between WHPA Delineation Methods and Criteria

CRITERIA / METHOD	DISTANCE (L/M/H)	DRAWDOWN (L/M/H)	TOT (L/M/H)	PHYSICAL BOUNDARIES (L/M/H)	ASSIMILA-TIVE CAPACITY (L/M/H)
ARBITRARY FIXED RADIUS	H	N/A	N/A	N/A	N/A
CALCULATED FIXED RADIUS	N/A	H	H	N/A	N/A
SIMPLIFIED VARIABLE SHAPES	N/A	N/A	M	N/A	N/A
ANALYTICAL MODELS	N/A	H	H	N/A	M
NUMERICAL FLOW/ TRANSPORT MODELS	N/A	H	H	N/A	M
HYDROGEOLOGIC MAPPING	H	N/A	N/A	H	N/A

L–LOW
M–MEDIUM
H–HIGH
N/A–NOT APPLICABLE

Table 4-5
WHPA Methods Selection Versus Technical Considerations

CRITERIA / METHOD	EASE OF APPLI-CATION L/M/H	EXTENT OF USE L/M/H	SIMPLI-CITY OF DATA REQUIRE-MENTS L/M/H	SUITABIL-ITY FOR HYDRO-GEOLOGIC SETTINGS L/M/H	ACCURACY L/M/H	RANKING (1-4)
ARBITRARY FIXED RADII						
CALCULATED FIXED RADII						
SIMPLIFIED VARIABLE SHAPES						
ANALYTICAL METHODS						
HYDROGEOLOGIC MAPPING						
NUMERICAL FLOW/ TRANSPORT MODELS						

L—LOW
M—MEDIUM
H—HIGH

NOTE: Ranking (1-4): 4 is most desirable, 1 is least desirable.

Accuracy. It is important to consider the degree to which the results from method application can be expected to compare with actual field conditions.

4.5.2 Policy Considerations

To aid in the process of selecting a method, an evaluation matrix of methods versus policy considerations is presented as Table 4-6. The matrix has been left blank, so that an appropriate ranking of each method may be made by a State or locality in its selection process. The policy considerations are described below.

Ease of Understanding. It is important to consider the degree to which the principles underlying the method can be readily understood by nontechnical people.

Economy of Application. The relative cost incurred in applying a method to one wellhead, well field, or the main fields in a State may do much to inhibit or encourage its use. Factors that may affect costs include data acquisition, professional labor, computer time, graphics, and reporting.

Defensibility. Enforcement and permitting considerations will require that the boundaries of a WHPA be clearly defined and defended against potential challenges and litigation from parties affected by the delineation.

Relevance to Protection Goal. As mentioned in subsection 3.3.1, WHPA delineation will reflect an overall policy/protection goal. The relevance to this goal of the methodology under consideration by the State is a key factor in program success.

Table 4-6
WHPA Method Selection Versus Policy Considerations

POLICY CONSIDERATION / METHOD	EASE OF UNDERSTANDING (L/M/H)	ECONOMY OF METHOD APPLICATION (L/M/H)	DEFENSIBILITY (L/M/H)	RELEVANCE TO PROTECTION GOAL (L/M/H)	RANKING (1-5)
ARBITRARY FIXED RADIUS					
CALCULATED FIXED RADIUS					
SIMPLIFIED VARIABLE SHAPES					
ANALYTICAL MODELS					
NUMERICAL FLOW/ TRANSPORT MODELS					
HYDROGEOLOGIC MAPPING					

NOTE: Ranking (1-5): 1 is most desirable, 5 least desirable

L–LOW
M–MEDIUM
H–HIGH
N/A–NOT APPLICABLE

CHAPTER 5

EXAMPLE OF CRITERIA AND METHOD SELECTION

An example of the steps that a regulating agency might consider in a WHPA delineation is provided in this chapter. The example is not meant to be the only appropriate procedure. The approach eventually selected must reflect the specific protection goal and other technical and policy considerations that a State might use in meeting the requirements of the Safe Drinking Water Act.

Variations and diversities exist in both hydrogeologic settings and State regulatory programs in the United States. Certain programs may find that their environmental policies and resources lend themselves to one procedure, while those elsewhere make another approach more suitable. Consequently, numerous issues should be thoroughly examined and evaluated. These include water supply well construction regulations and practices in use; organizational and institutional capabilities of State and local agencies to provide appropriately skilled personnel, equipment, materials, and implementation funding; and type and complexity of the hydrogeologic settings in the State. A careful examination of these matters will greatly facilitate selection of the most appropriate delineation criteria, methodologies, and strategies for implementation. Guidance on these management-related issues is provided in other resource documents prepared by EPA.

The example of the criteria and method selection process for the hypothetical State is organized in the following manner:

- Description of the WHPA delineation problem
- Evaluation matrices for degree of protection, technical, and policy considerations
- Summary of final decision reached by the hypothetical State.

5.1 PROBLEM STATEMENT: THE HYPOTHETICAL STATE

The hypothetical State is establishing a wellhead protection program under the SDWA. A panel of experts has been established with both technical and nontechnical expertise. The panel's work was conducted under the following assumptions, developed by previous State planning and research:

- Aquifers requiring the greatest protection are mostly unconfined aquifers comprised of unconsolidated sands or sands and gravels.

- Certain industries will be affected by the WHPA program, and the threat of litigation has been raised. The technical basis of the WHPA delineation program may, therefore, be challenged.
- It is estimated that available technical personnel from State agencies will be able to perform all analyses and mapping of the WHPA's in an expedient manner.
- Degree of protection considerations have established that the goal of WHPA delineation will be to provide management of the well-field area. It is expected that three different protection zones will be established to protect against each type of threat (physical, microbial, and chemical). These will be labeled Zones I, II, and III, respectively.
- Approximately 900 wellheads will be in the first phase for delineation relative to chemical threats (i.e., Zone III).
- A program to inform the general public of the developing wellhead protection efforts will be implemented.
- The State, in cooperation with county and local agencies, has the authority to impose land use controls within the zones.

5.2 EXAMPLE OF CRITERIA SELECTION

5.2.1 Overall Protection Goals

As noted in the problem statement, the hypothetical State's goal is to provide management of the well-field area. The panel was asked to examine and recommend delineation criteria based on both technical and policy considerations. These separate analyses, in addition to the panel's final recommendations, are outlined below.

5.2.2 Technical Considerations

As noted in the problem statement (subsection 5.3.2), most of the aquifers requiring protection in the hypothetical State are unconfined, porous media units. Based on this, the panel evaluated the technical merits (subsection 3.4.3) of the delineation criteria, focusing primarily on the 900 high-priority wells. The completed evaluation matrix is illustrated as Table 5-1.

Based on this evaluation, the panel decided that the criterion providing the strongest technical basis for WHPA delineation was TOT, with a threshold value of 15 years. The

Table 5-1
WHPA Criteria Selection Versus Technical Considerations
(Water Table Aquifer in Porous Media for the Hypothetical State Example)

TECHNICAL CONSIDERATION / CRITERIA	EASE OF APPLICATION L/M/H	EASE OF QUANTIFICATION L/M/H	VARIABILITY UNDER ACTUAL CONDITIONS L/M/H	EASE OF FIELD VERIFICATION L/M/H	ABILITY TO REFLECT GROUND-WATER STANDARD L/M/H	SUITABILITY FOR A GIVEN HYDROGEOLOGIC SETTING L/M/H	ABILITY TO INCORPORATE PHYSICAL PROCESSES L/M/H	RANK (1 TO 5)
DISTANCE	H	H	H	H	N/A	L	L	1
DRAWDOWN	M	H	L	H	N/A	H	L	2
TIME OF TRAVEL	M	M	L	L	M	H	H	5
FLOW BOUNDARIES	M	N/A	H	H	N/A	M-H	M	4
ASSIMILATIVE CAPACITY	L	L	H	L	H	M-H	M	3

L – LOW
M – MEDIUM
H – HIGH
N/A – NOT APPLICABLE
Selected Criterion

NOTE: Ranking (1-5): 5 is most desirable, 1 is least desirable relationships between the TOT criterion (and the other criteria) and each of the technical considerations are summarized by the rankings in Table 5-1 and are detailed below.

Ease of Application. Ease of application was not judged to be a significant impediment in the hypothetical State. The State's technical staff was deemed capable of understanding and applying TOT information as a delineation criterion. Though the application will be relatively complex (rated "M" in the matrix), the panel determined it to be within the State's capabilities and allotted time.

Ease of Quantification. Although TOT is more difficult to quantify than other criteria, the hypothetical State's panel of experts believed that workable, technically defensible thresholds for the TOT criteria can be established and applied. These will focus on the need to protect wellheads from microbial and chemical threats. The panel concluded that a minimum of a 50-day TOT (along with a minimum distance of 500 feet) is needed to protect against microbial contamination (Zone II). A 15-year TOT was seen as an appropriate threshold to protect the well against the threat of chemical contamination (Zone III). Most water purveyors purchase the land immediately contiguous to the well, typically up to 100 feet away, which effectively delineates Zone I).

Variability Under Prevailing Conditions. The panel recommended that the WHPA delineation effort should accommodate future changes in pumping patterns. The panel concluded that selected criteria should allow adjustments to the size of the WHPA to allow for the effects of future increases in pumping rates; a TOT criterion will allow for this adjustment. The projected maximum pumping capacity of existing wells under some drought conditions will therefore be factored into the analysis to reduce the need to expand the WHPA's in the near future.

Ease of Field Verification. It is not anticipated that field verification of zones of TOT's will be undertaken for the whole State. Measurements will be done at several test case sites. These measurements will be extrapolated to other WHPA's with similar hydrogeologic conditions in the State.

Ability to Reflect Ground-Water Standards. The panel recognized that the attentuation capacity of the aquifers for specific contaminants could theoretically be assessed. The panel felt this criterion was impractical to implement, except for some experimental studies. They also doubted that high-flow sand and sand and gravel aquifers within the State could be protected by this criterion.

Suitability for Hydrogeologic Settings. Use of a TOT criterion to delineate WHPA's in a water table aquifer in porous media was deemed appropriate, since most of the approaches developed to estimate TOT's are based on assumptions that are generally met in these aquifers within the State.

Ability to Incorporate Physical Processes. Most physical processes involved in the transport of contaminants in a porous media aquifer, such as advection and dispersion, are incorporated in TOT. This criterion is thus quite applicable for this type of aquifer.

5.2.3 Policy Considerations

The hypothetical State's panel also evaluated the five criteria with respect to several policy considerations and a composite ranking was established, as illustrated in Table 5-2. For these considerations, a distance criterion was actually judged to be somewhat superior to TOT. The panel's rationale for this ranking is discussed below, and the resolution of this issue provided in subsection 5.2.4.

Ease of Understanding. The ability of the general public to understand the criterion was considered important. Distance was judged to be the easiest to understand ("H" rating on the matrix). However, it was believed that more technical concepts such as TOT could be explained to the public.

Economy of Criteria Development. Development of a distance criterion would be very economical. However, the panel concluded that, were this criterion ultimately selected for the State, the threshold values selected should have some scientific basis. It was also considered desirable to be somewhat "over-protective" (i.e., larger dimensions), given the problems with the scientific basis. Implementation problems due to extension of regulating authority over large geographic areas were a related concern.

Defensibility. The panel was concerned by the lack of technical justification for a distance criterion. Since the thresholds required to provide adequate protection would likely be overly "conservative" (i.e., overprotected), challenges from affected parties were considered possible.

Usefulness for Implementing Phasing. The panel concluded that the distance criterion would be very useful for the State as an initial step if a phasing approach were to be used. In a few years the State could move to a more sophisticated criterion. However, phasing had already been eliminated to avoid enforcement problems and the difficulties of defending arbitrarily determined areas.

Table 5-2
WHPA Criteria Selection Versus Policy Considerations

POLICY CONSIDERATION / CRITERIA	EASE OF UNDER-STANDING (L/M/H)	ECONOMY OF CRITERIA DEVELOPMENT (L/M/H)	DEFENSIBILITY (L/M/H)	USEFULNESS FOR IMPL-MENTING PHASING (L/M/H)	RELEVANCE TO PROTECTION GOAL (L/M/H)	RANKING (1-5)
DISTANCE	H	H	L	M	M	5
DRAWDOWN	M	M	M	L	M	3
TOT	M	M	H	M	M	4
FLOW BOUNDARIES	L	M	L	L-M	M-H	2
ASSIMILATIVE CAPACITY	L	L	L	L-M	L	1

NOTE: Ranking (1-5): 5 is most desirable, 1 is least desirable.

L–LOW
M–MEDIUM
H–HIGH
N/A–NOT APPLICABLE

Relevance to Protection Goal. Given the hydrogeologic settings in the State, and the other assumptions outlined above, most criteria were acceptable. The key decision was believed to be the selection of criteria thresholds.

5.2.4 Summary of Panel's Decision on Criteria Selection

The example for the hypothetical State illustrated can various considerations affect the ultimate selection of criteria. A TOT criterion was eventually chosen after weighing technical and policy considerations together. Though policy issues might have led to the selection of distance as a criterion, TOT was rated nearly as high. The deciding factors for this State were the concern over legal challenges, the relatively "simple" hydrogeologic settings (enhancing the utility of TOT), and the fact that technical resources in the State were deemed adequate. Therefore, the ultimate decision was to select a TOT criterion as the basis for WHPA delineation. The State established a minimum of 15 years TOT as the threshold value. Municipalities and counties were urged to adopt more protective thresholds (e.g., 20- to 50-year TOT's) where feasible.

5.3 EXAMPLE OF METHOD SELECTION

This section presents an example of how the panel of experts from the hypothetical State evaluated the choices of available methods for mapping WHPA's. Given the panel's previous recommendations on WHPA criteria, evaluations and rankings were only made for methods that could map a TOT criterion (Table 4-3).

The panel again assessed the choices with respect to both technical and policy considerations. The four methods that would map the selected criterion (TOT) were evaluated with respect to technical evaluation factors, described in subsection 4.5.1. The results of their rankings are presented in Tables 5-3 and 5-4. As shown in these matrices, the panel preferred analytical flow and transport models. The technical reason for this method preference was based largely on the absence of flow boundaries near the pumping wells. If the effects of boundaries on WHPA delineation had been considered, the panel would have ranked numerical flow/transport models higher than the selected method. An additional factor influencing the panel's ranking was the conclusions obtained by the State through comparative studies of WHPA delineations, performed at a few selected test sites. These studies indicated that the results from analytical flow/transport models correlated well with results from the more sophisticated methods (such as numerical flow/transport models and hydrogeologic mapping). Therefore, the less complex and more economical method was selected.

Table 5-3
WHPA Methods Selection Versus Technical Considerations
(Water Table Aquifer in Porous Media for the Hypothetical State Example*)

CRITERIA / METHOD	EASE OF APPLI-CATION L/M/H	EXTENT OF USE L/M/H	SIMPLI-CITY OF DATA REQUIRE-MENTS L/M/H	SUITABIL-ITY FOR HYDRO-GEOLOGIC SETTINGS L/M/H	ACCURACY L/M/H	RANKING (1 - 5)
ARBITRARY FIXED RADII						N/A
CALCULATED FIXED RADII	H	M	H	L	L	4
SIMPLIFIED VARIABLE SHAPES	M–H	L	H	H	L–M	2
ANALYTICAL FLOW TRANSPORT MODELS	L–M	H	M	H	M	5
HYDROGEOLOGIC MAPPING	L–M	M	L–M	H	M–H	1
NUMERICAL FLOW/ TRANSPORT MODELS	L	L–M	L–M	H	M–H	3

L–LOW
M–MEDIUM
H–HIGH
T–TECHNICAL
N–NON-TECHNICAL
N/A–NOT APPLICABLE

NOTE: Ranking (1 - 5): 5 is most desirable, 1 is least desirable.

* The ranking is based on a previous selection of TOT as the criterion. Other criteria selections may influence ranking.

Table 5-4

WHPA Method Selection Versus Policy Considerations

(Water Table Aquifer in Porous Media for the Hypothetical State Example*)

POLICY CONSIDERATION / METHOD	EASE OF UNDERSTANDING	ECONOMY OF METHOD APPLICATION	USEFULNESS FOR ENFORCEMENT	RELEVANCE TO PROTECTION GOAL	RANKING (1-5)
ARBITRARY FIXED RADII				L	N/A
CALCULATED FIXED RADII	M-H	M-H	L	L	4
SIMPLIFIED VARIABLE SHAPES	M-H	M-H	L-M	L	3
ANALYTICAL FLOW MODELS	L-M	M	M	H	5
HYDROGEOLOGIC MAPPING	L-M	M	M-H	M	1
NUMERICAL FLOW/TRANSPORT MODELS	L	L-M	M-H	M	2

NOTE: Ranking (1 - 5): 5 is most desirable, 1 is least desirable.

L–LOW
M–MEDIUM
H–HIGH
N/A–NOT APPLICABLE

Selected Criterion

*The ranking is based on previous selection of TOT as the criterion. Other criteria selection and other state conditions would lead to different rankings.

From the standpoint of policy considerations, and in particular relevance to the protection goal, analytical models were clearly preferred over numerical procedures. The latter, if used for all wells, would be prohibitively expensive and would prevent the State from meeting its statutory responsibilities.

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APPENDIX A

WHPA DELINEATION APPROACHES

There are many examples of wellhead protection programs in the United States and Europe. The structure and scope of these programs vary and reflect differing demographic, political, and hydrogeologic conditions. Some states and municipalities have developed wellhead protection as part of overall ground-water protection programs. The main focus of these programs is the delineation of wellhead protection areas that impose land use controls to protect public water supply wells.

A.1 STATE EXAMPLES

As part of EPA's research on wellhead protection, numerous state programs were examined for technical aspects of their WHPA delineation effort. Six common methods for WHPA delineation were identified, as well as many specific techniques for applying them to local situations. These methods are listed together with associated criteria and locations where they are applied.

The methods identified in Table A-1 range in sophistication from those that can be applied by non-technical professionals (e.g., arbitrary fixed radius) to very complex methods that require technical specialists (e.g., numerical flow/transport models). The following is a brief review of wellhead protection activities in four selected states. While not exhaustive, this review gives an indication of existing State and local programs.

A.1.1 State of Florida

Several of Florida's County governments have sophisticated ground-water protection programs. The State has also passed amendments to Chapter 17-3 of the Florida Administrative Code that establishes a State-wide wellhead protection program for vulnerable aquifers. The program would require wellhead protection zones to restrict activities that could contaminate the ground water.

The proposed law establishes two protection zones around public drinking water supplies that have an average daily withdrawal of at least 100,000 gallons of ground water. The zones are defined as two concentric areas around the major public water supply well(s) or well field(s) of 200 feet and 5 years ground-water travel time, respectively. The 5-year TOT zone is defined with an analytical volumetric equation, a concept explained in Section 4 and Appendix B.

TABLE A-1

State WHPA Delineation Methodologies and Criteria

Method	Criteria Relied on	Selected Locations Where Used*
Arbitrary Fixed Radius	Distance	Nebraska Florida Edgartown, MA Duxbury, MA
Calculated Fixed Radius	Distance Time of Travel	Florida
Simplified Variable Shapes	Time of Travel Drawdown	Southern England
Analytical Flow Model	Drawdown Physical Features	Cape Cod, MA Duxbury, MA Edgartown, MA West Germany Holland
Geologic/Geomorphic	Physical Features	Vermont Connecticut Duxbury, MA
Numerical Flow/Transport Model	Time of Travel Drawdown	Dade Co., FL Broward Co., FL Palm Beach, FL

* or being considered

Within these concentric zones, discharges into the ground-water from stormwater systems, underground storage facilities, underground product pipelines, and other sources are subject to varying degrees of control depending on their proximity to the wellhead. For example, the proposed law prohibits new discharges and new installations within the 200-foot zone of protection. Within the 5-year zone of protection, new discharges from several types of facilities are subject to control and monitoring requirements. New discharges of industrial wastes that contain hazardous constituents are prohibited and new discharges of treated domestic waste effluents are allowed, provided a number of conditions are met.

A.1.2 Dade County, Florida

Dade County has developed a comprehensive wellhead protection program, consisting of five elements: water management, water and wastewater treatment, land use policy, environmental regulations and enforcement, and public awareness and involvement. The program applies to an array of prohibitions, restrictions, permit requirements, land use tools, and management controls designed to protect all of Dade County's public water supply wells from contamination by the approximately 900 substances which the County has identified as hazardous. Features of the program include:

- Delineation of recharge areas around wellfields using numerical computer models with some in-field verification through monitoring of head relationships
- Application of land-use restrictions within the recharge areas and the designated wellfield protection zones
- Public education programs
- Establishment of water treatment programs
- Development of water management and pollutant source control regulation.

Where the State of Florida defines two concentric protection zones, Dade County establishes three. The inner two are delineated as 30- and 210-day TOT's. The outermost zone is the larger of either a 500-day TOT or a 1-foot drawdown. The largest WHPA, approximately 7 miles across, is associated with the Northwest Wellfield.

Furthermore, Dade County maintains a computerized inventory of contaminant sources, and issues approximately 10,000 operating permits per year to recognized, nonresidential users within the delineated wellfield protection zones.

A.1.3 Massachusetts

The Commonwealth of Massachusetts does not require extensive WHP (except for microbial threats), but does incorporate the concept as an option, and fosters it through the Aquifer Land Acquisition Program (ALA). The goals of the program are to help local officials define the primary water recharge areas around public water supply wells, to work with local officials to properly address land uses within the recharge areas of these wells, and to reimburse eligible applicants for land acquired in key segments of recharge areas for water supply protection purposes. The program encourages a mix of strategic land acquisition and effective land use controls to achieve water well protection.

As part of the program, the Massachusetts Department of Environmental Quality Engineering (DEQE) has defined three zones of contribution that compose the total recharge areas for a public well. Theoretically these three zones constitute the geographic area in which land uses may affect the drinking water supply well.

- Zone 1, the 400-foot radius or other designated area surrounding a water supply well, must be in compliance with the DEQE Drinking Water Regulation (310 CMR 22.00).
- Zone II is the area of an aquifer that contributes water to a well under the most severe recharge and pumping conditions that can be realistically anticipated. It is bounded by the ground-water divides that result from pumping the well, and by the edge of the aquifer with less permeable materials such as till and bedrock. At some locations, streams and lakes may form recharge boundaries.
- Zone III is that land area beyond the area of Zone II from which surface water and ground water drain into Zone II. The surface drainage area as determined by topography is commonly coincident with the ground-water drainage area and will be used to delineate Zone III. In some locations, where surface and ground-water drainage are not coincident, Zone III shall consist of both the surface drainage and the ground-water drainage areas.

The delineation and management of these three zones form the basis of an ALA grant program through which local governments compete to obtain funds from the State to purchase land for water well protection purposes.

The Commonwealth has restricted the reimbursement for land purchases to Zone II. The rationale for this decision was that Zone II areas consist of relatively permeable surficial deposits and represent the area of the municipality in which land uses have the greatest potential for adversely impacting the local water wells(s). Zone I was eliminated from the reimbursement scheme because under Massachusetts law the water supplier is already required to control land use within the 400-foot radius surrounding the well. It should be noted, however, that land purchase is used primarily as an incentive to foster participation in the program. Even with some of the small glacial aquifers in the State, a minor portion of the land in the recharge area can be purchased. The key protection is afforded by the adoption of ordinances, which the State requires for acceptance of ALA grants.

The program requires applicants to supply four major categories of information: aquifer/water supply information, land use information, resource protection plans, and land acquisition information. Under the first category, Zones I, II, and III must be delineated and mapped. Any pump tests or modeling used to delineate zones must be documented.

Some level of land use information must be supplied for all three zones. All major land use activities such as commercial, residential, agricultural, and industrial uses in Zone II must be mapped and public transportation corridors identified. For areas in Zone III, only those land use activities that pose significant threats to ground water—such as hazardous waste sites, surface impoundments, landfills, auto junkyards, underground storage tanks, salt storage sheds, and sand and gravel operations—need be documented.

Information on a water resources protection strategy that identifies existing and/or proposed land use controls designed to protect the supplies must be included in the submittal for the suggested land and/or easement purchase. The State uses this information to determine whether there is a sound basis for the locality acquiring the land and whether the town will indeed be able to complete the land acquisition should an award be granted.

All applications are ranked and prioritized based on two major criteria: the value and use of the resource and the degree of resource protection that can be expected from the proposed water protection strategy.

A.1.4 Vermont

The State of Vermont is developing a Statewide wellhead protection program. As part of this, the Agency for Environmental Conservation (AEC) is developing regulations that will be used to map the cones of influence, the primary recharge areas, and the secondary recharge areas of water wells in Vermont. These maps will be used by AEC and other regulatory agencies in their permitting activities.

One set of tools currently available to State regulatory agencies making management decisions are the existing maps of recharge areas or Aquifer Protection Areas that were delineated in the Vermont Aquifer Protection Area (APA) Project in the 1970's. The project resulted in 209 individual APA's located in 104 Vermont towns. An APA is defined as the land surface area that encompasses the recharge, collection, transmission, and storage zones for a town's well or spring.

Eight categories of APA's were delineated based on hydrogeologic factors:

- Wells in unconfined and leaky unconsolidated aquifers with available engineering pump tests
- Wells in unconfined and leaky unconsolidated aquifers without engineering pump tests
- Wells in confined unconsolidated aquifers
- Bedrock wells, using an infiltration model
- Bedrock wells, using a leakage model
- Springs in unconsolidated material and at the interface between unconsolidated material and bedrock, with high relief in the upgradient direction
- Springs in unconsolidated material and at the interface between unconsolidated material and bedrock, with low relief in the upgradient direction
- Springs emanating from bedrock.

There are no regulations associated with mapped APA's, but Vermont's existing regulatory programs use APA's to flag areas needing special consideration during the review process on development applications.

A.2 EUROPEAN DELINEATION APPROACHES

At least 11 European countries have developed ground-water protection programs comparable to the WHPA concept (Figure A-1). The European Community (EC) Directive on the Protection of Groundwater Against Pollution Caused by Certain Dangerous Substances (80/63/EC), issued in December 1979, requires member states to protect (by law, regulation, and administrative provision) all usable ground waters against direct and indirect discharges of certain listed substances. However, ground-water protection programs in Europe significantly predate this directive. Development of policies to prevent movement of contaminants into the subsurface environment began in the last century, through the most important laws and regulations date to the 1950's. West Germany and the Netherlands have the most extensive experience in this area, and their programs are described here.

European programs generally involve the delineation of at least three zones of protection, defined by distance and/or TOT. These are more or less concentric rings, starting with the area immediately around the wellhead. Typically, an outermost zone is drawn to the recharge area boundary. Within these zones, restrictions are imposed on a number of activities including, but not limited to do, waste disposal sites, the transport and storage of hazardous chemicals, waste water disposal, and the application of leachable pesticides. The degree of restriction decreases as the distance from the wellhead increases.

A.2.1 The Netherlands

The Netherlands delineates three or more zones of protection, based on aquifer type (van Waegeningh, 1985 and 1987). These zones are generally defined using analytical models whose applications require some degree of technical expertise. When the effort began, simple fixed-radius approaches were used. Analytical methods are now the most widespread approach. Numerical models for WHPA assessment around key wells are increasingly common, though analytical methods are still used for the areas closest to the pumping wells (Heij, 1987). The first protective area lies immediately around the wellhead, up to 30 meters away, and is purchased by the water authority. The second zone is defined by a 60-day TOT, and is designed to protect the well from microbial

Figure A-1
European Protection Areas

Germany Fed. Rep.	Austria	Belgium	Finland	Netherlands	France	Czechoslovakia	Switzerland	Hungary	Sweden	German Dem. Rep.
Zone I Well field 10 - 100 m	Protection area	Immediate protection zone 100m 24hrs.	Intake area	Catchment area	Immediate protection (10 - 20m)	Primary sanitary protection zone 10 - 50 m	Zone I 10 - 20 m	Protection zone	Well area	Zone I 5 - 100 m
Zone II		Inner protection area	Inner protection zone		Inner protection area	Internal secondary sanitary protection zone	Zone II		Inner protection area	Protection Zone II
50 days	50 days	(300-100m) 50 days	60 days	(> 30m) 50 - 60 days			10 days > 100m	50 days -	> 60 days > 100m	60 days
Zone III A 2 km	Partial protection area	Remote protection area	Outer protection zone	Protection area, 10 years delay	Remote protection area	External secondary sanitary protection zone	Zone III A 200 m	Hydro-geological protection area	Outer protection area	Zone III A 10 years
				Protection area, 25 years delay				25 - 100 years delay		Zone III B 25 years
Zone III B				Far recharge area			Zone III B	Regional protection		

OUTER BOUNDARY OF RECHARGE AREA

SOURCE: Van Waegeningh, 1985

contaminants. There is then a "water protection" area, roughly comparable to the WHPA boundaries. This is subdivided into areas within 10-year and 25-year TOT, roughly 800 and 1,200 meters from the well in the Netherlands. An outermost zone, the "far recharge area," is delineated to the outer boundary of the well recharge area.

A.2.2 West Germany

The West German wellhead protection strategy, though it was developed first, is quite comparable to the Dutch approach, and also depends largely on analytical solutions. Zone I covers the immediate wellhead area, to a radius of 10 to 100 meters. Zone II is delineated by a 50-day TOT. The "water protection area," Zone III, is subdivided into inner and outer areas. Zone III A extends up to 2 kilometers from the well (if the aquifer boundaries are more distant). Zone III B extends to the outer boundary of the recharge area. Since many aquifers are contained within sedimentary basins, hydrogeologic mapping and numerical simulation procedures are used in a basin-by-basin approach.

APPENDIX B

COMPARATIVE ANALYSIS

Comparative analyses of WHPA methods were presented in Chapter 4 as a valuable approach for State wellhead protection. This appendix provides examples of comparative analyses of method applications for wells in Massachusetts, southern Florida, Colorado, and Connecticut. Each comparative analysis focused on an existing or proposed well or well field. The sites chosen all had some WHPA delineation already in place or in process. The State, county, or locality that performed WHPA delineation utilized the method of its choice. Criteria and criteria thresholds varied, depending on specific program goals. To complete these analyses as method comparisons, additional approaches were applied. The four basic methods used were:

- Calculated fixed radius (CFR), based on the State of Florida's approach
- Analytical methods
  - Uniform flow model
  - Strahler prism model
- Numerical model.

The comparative analyses present examples of delineation method selections as they might be encountered in "real world" situations. The analyses compared WHPA's delineated by different methods for a single well or well field and one set of hydrogeologic parameters. Direct comparison of areas resulting from each of these methods should be made with a understanding that the areas being compared may represent different types of zones. For example, as discussed in Chapter 4, the area resulting from applying the uniform flow model is the zone of contribution of the well, whereas areas resulting from application of numerical models (particularly as presented in this appendix) yield zones of influence or zones of transport. These comparisons are based on the assumption that the numerical model yields the most "accurate" delineations of WHPA's. Therefore, comparisons use the WHPA resulting from the numerical methods as the standard.

In each case study, different delineation methods were used for individual well(s) using the same or very similar hydrogeologic parameters. The delineation methods used in the comparative analysis and the type of data required by each method are shown in

Figure B-1. Given the varying criteria thresholds chosen by the various government bodies, it was not possible in this assessment to consider the same criteria and methods for all cases.

Methods and criteria thresholds used in these comparative analyses have not been endorsed or approved by EPA. The analyses presented here are intended only to demonstrate a valuable procedure, rather than to endorse or critique any specific delineation method. In addition, these analyses are not meant to support or critique the WHPA delineation criteria or methods chosen by the State or locality. Furthermore, numerous assumptions were made that may affect the accuracy of the WHPA boundaries shown. The results should therefore not be used to judge WHP in these specific areas.

Figure B-1
Data Requirements for WHPA Methods Used in Comparative Analysis

Application Method	Data Requirements: K	T	Q	n	i	H	S	α	R	Hydrologic Boundaries	Aquifer Geometries
Calculated fixed radius			X	X		X					
Uniform flow model	X		X	X	X	X					
Strahler prism model		X	X		X	X	X		X		
Numerical model	X		X	X		X	X	X	X	X	X

PARAMETERS	NOMENCLATURE	DIMENSIONS
Hydraulic Conductivity	K	L/T
Transmissivity	T	L^2/T
Pumping Rate	Q	L^3/T
Porosity	n	dimensionless
Hydraulic Gradient (Regional)	i	dimensionless
Saturated Thickness	H	L
Storage Coefficient (Specific Yield)	S	dimensionless
Dispersivity	α	L
Longitudinal	α_ℓ	L
Transverse	α_t	L
Recharge	R	L/T

B.1 CAPE COD, MASSACHUSETTS

B.1.1 Hydrogeology of Study Area

The principal water-bearing formations on Cape Cod, predominantly unconsolidated sands and gravels, are parts of a coastal complex of end moraines and outwash plains. The study area's major geologic formations include the Mashpee pitted outwash plain deposits, the Buzzards Bay moraine deposits, and the Buzzards Bay outwash deposits. The majority of the study area is situated over the Mashpee pitted outwash plain. The surficial outwash deposits are composed of fluvially-bedded gravels and gravelly sands deposited following recession of the Cape Cod Bay and Buzzards Bay lobes. At depth, silty sands and till have also been identified. Recharge to the ground-water system is provided primarily through precipitation during the winter and spring seasons. Typically, the study area averages 43 inches of precipitation annually, with reported estimates of annual recharge to the ground-water system between 12 and 24 inches. Remaining precipitation is lost through evapotranspiration; a small portion is lost through direct runoff to streams, ponds, and swamps.

B.1.2 Method Application

WHPA delineation methods used in the Cape Cod comparative analysis included (1) a calculated fixed radius method, (2) two analytical methods (the uniform flow model and the Strahler prism model), and (3) a numerical model. Comparative analyses of delineated areas were done for two wells.

Calculated Fixed Radius. The calculated fixed radius (CFR) method used was the Florida Department of Environmental Resources volumetric flow equation (De Han, 1986). WHPA's delineated with the CFR equation were delineated based on travel-time criteria of 10, 25, and 50 years.

Analytical Methods. The first analytical method used was the uniform flow model (Todd, 1980) (see Chapter 4). The model was used to estimate the downgradient and lateral extent of the WHPA's. The upgradient boundaries for these examples were determined using 10-, 25-, and 50-year TOT distances determined from a travel time equation used in England (see Chapter 4). The second analytical method applied, the Strahler prism model (Horsley, 1983) combines analytical and graphical techniques (Chapter 4). With this method, distances to downgradient and upgradient WHPA boundaries were determined using distance-drawdown curves, and a model developed for ground-water flow on Cape Cod. The WHPA's were then delineated as the areas supplying surface recharge to the pumping wells, with the calculated downgradient and upgradient bounds being the delineated area of recharge.

Numerical Method. WHPA's delineated with the numerical model were obtained from a 1985 study in which time-dependent (10-, 25-, and 50-year) ZOC's were delineated for six wells in the area (Camp, Dresser, and McKee, 1986), using a three-dimensional finite element model for ground-water flow and transport.

B.1.3 Data Requirements

Data used in the CFR and analytical methods are listed in Table B-1. These parameters reflect only hydrogeologic properties of the aquifer near the wells. These are at best global approximations to the spatially varying parameters. In contrast, the numerical model can take into account aquifer heterogeneities and the impact of flow boundaries (such as lakes and streams) in the area of WHPA delineation. The spatially changing parameters in the model are described in the original report by CDM (1986).

B.1.4 Comparison of Resulting WHPA's

Figures B-2 through B-7 show the delineated WHPA's for the two wells on Cape Cod using the CFR equation, the numerical model, the uniform flow model, and the Strahler prism model. For well 1 (Figures B-2 through B-4) the uniform flow model provided the largest area of coverage for TOT's of 10, 25, and 50 years. The Strahler prism model provided less coverage than the numerical model for a 50-year TOT, although the overlap with the numerical model was considerable. In several comparisons, the CFR equation was found to delineate the smallest area, and is therefore the least accurate of the methods. In addition, the CFR equation was less accurate as the criteria threshold increased. These deviations from the standard WHPA can be attributed to the fact that the CFR equation does not account for conditions of a sloping water table (i.e., gradient is not one of the parameters in the equation).

In the case of well 2, the uniform flow model provided results comparable to the numerical model, as is shown in Figures B-5 through B-7. The relative accuracy of the results is apparently due to the smaller effect of flow boundaries (such as surface water bodies) on ground water near the well. The uniform flow model provided the largest area of coverage, followed by the Strahler method. Both of these methods provided a larger area of coverage than the numerical model, with a high degree of commonality. As with well 1, the CFR equation was found to provide the least area, although it relatively better for the smaller TOT's. This probably reflects the regional slope of the water table.

Table B-1

Hydrogeologic Parameters Used in Comparative Analyses

	Massachusetts		Florida	Colorado	Connecticut
PARAMETER	VALUE FOR WELL 2	VALUE FOR WELL 1	VALUE	VALUE	VALUE
K (ft/day)	125	50	67	64	180
T (gpd/ft)	70,125	46,750	150,000	28,723	87,516
Q (mgd)	1	1	1.0*	0.41	2.4
n	.3	.3	0.2	0.18	0.2
i	.002	.0033	N/A	0.0095	0.005
H (ft)	75	125	300	60	65
S	.25	.25	N/A	N/A	N/A
α_ℓ	30	30	N/A	N/A	N/A
α_t	3	3	N/A	N/A	N/A
R (in/yr)	18	18	8-12	0.7	24

Note: Nomenclature on Figure B-1

*Pumping rate per well (3 wells total).

Figure B-2
WHPA Comparative Analysis, Example for Well # 1 Cape Cod, MA, 10-Year TOT

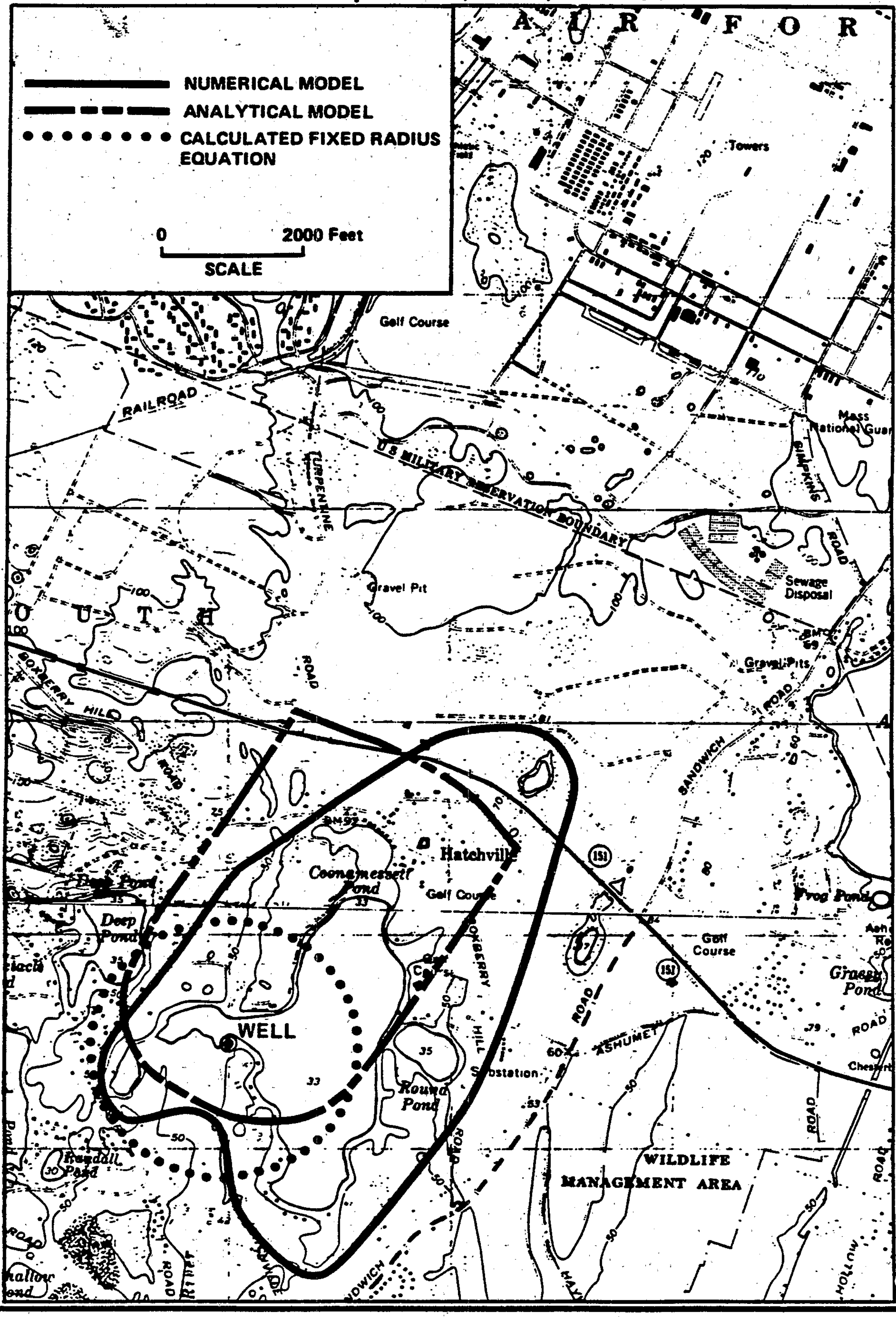


Figure B-3
WHPA Comparative Analysis, Example for Well #1 Cape Cod, MA, 25-Year TOT

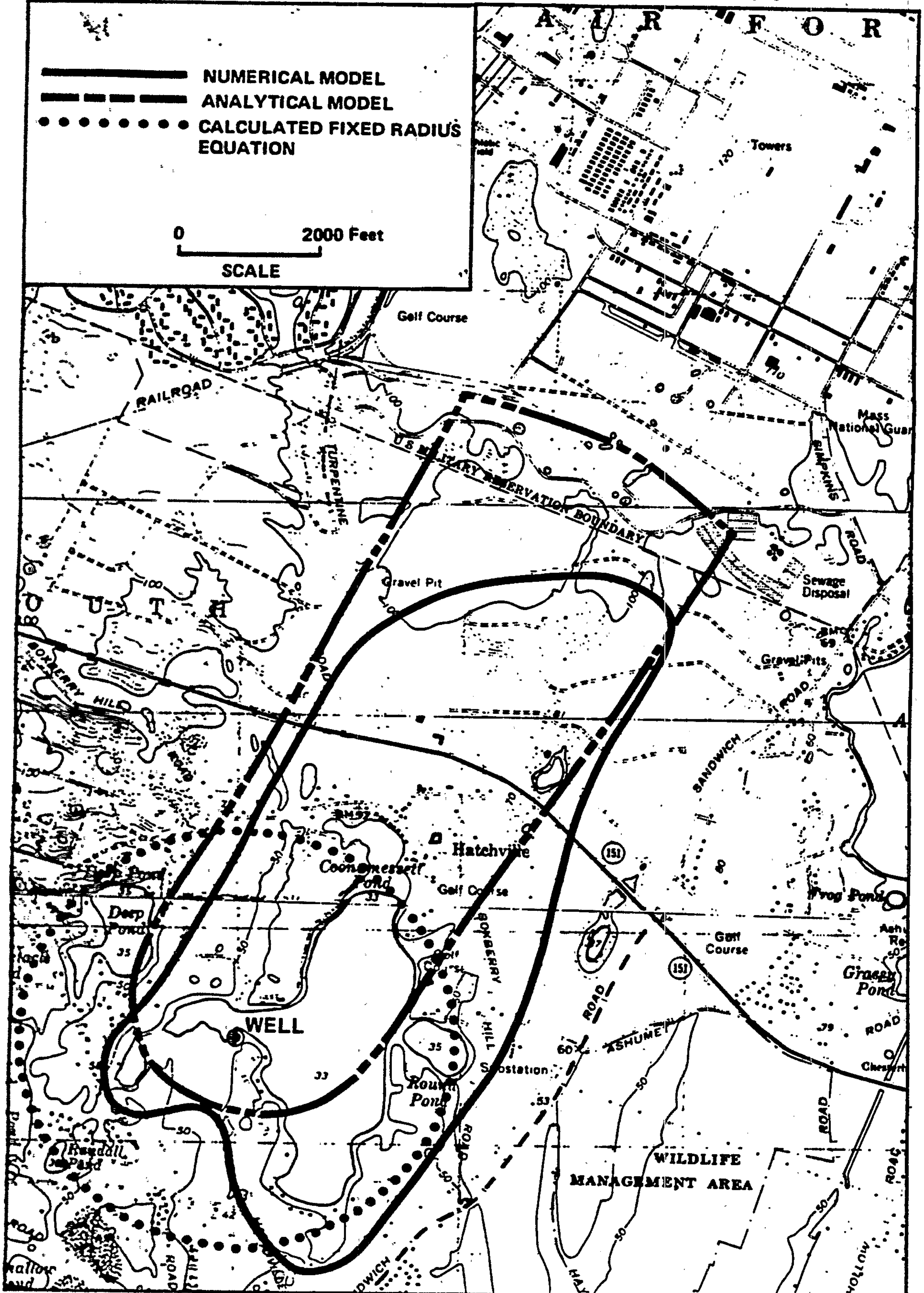


Figure B-4
WHPA Comparative Analysis, Example for Well #1 Cape Cod, MA, 50-Year TOT

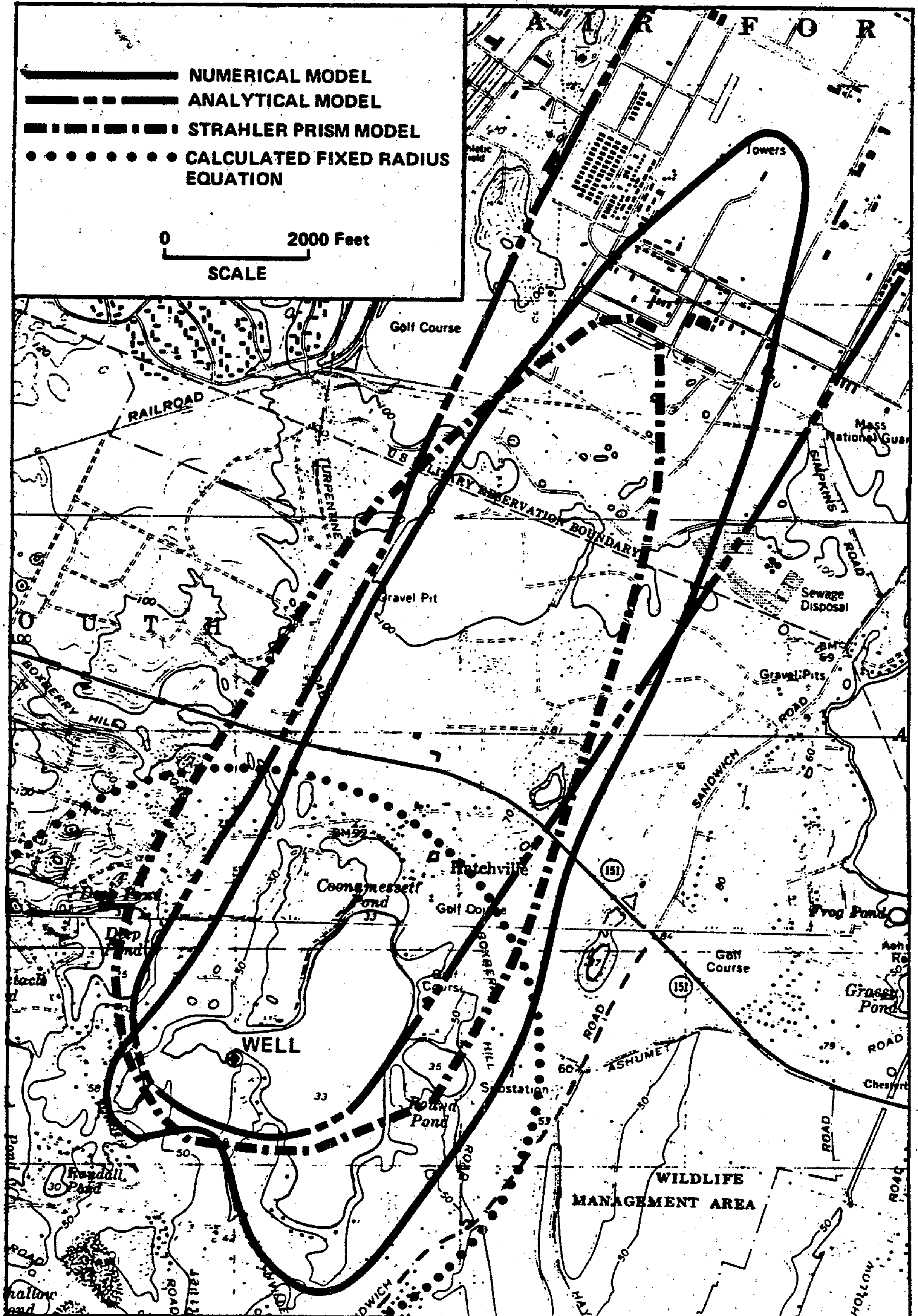


Figure B-5
WHPA Comparative Analysis Example for Well #2 Cape Cod, MA 10 Year TOT

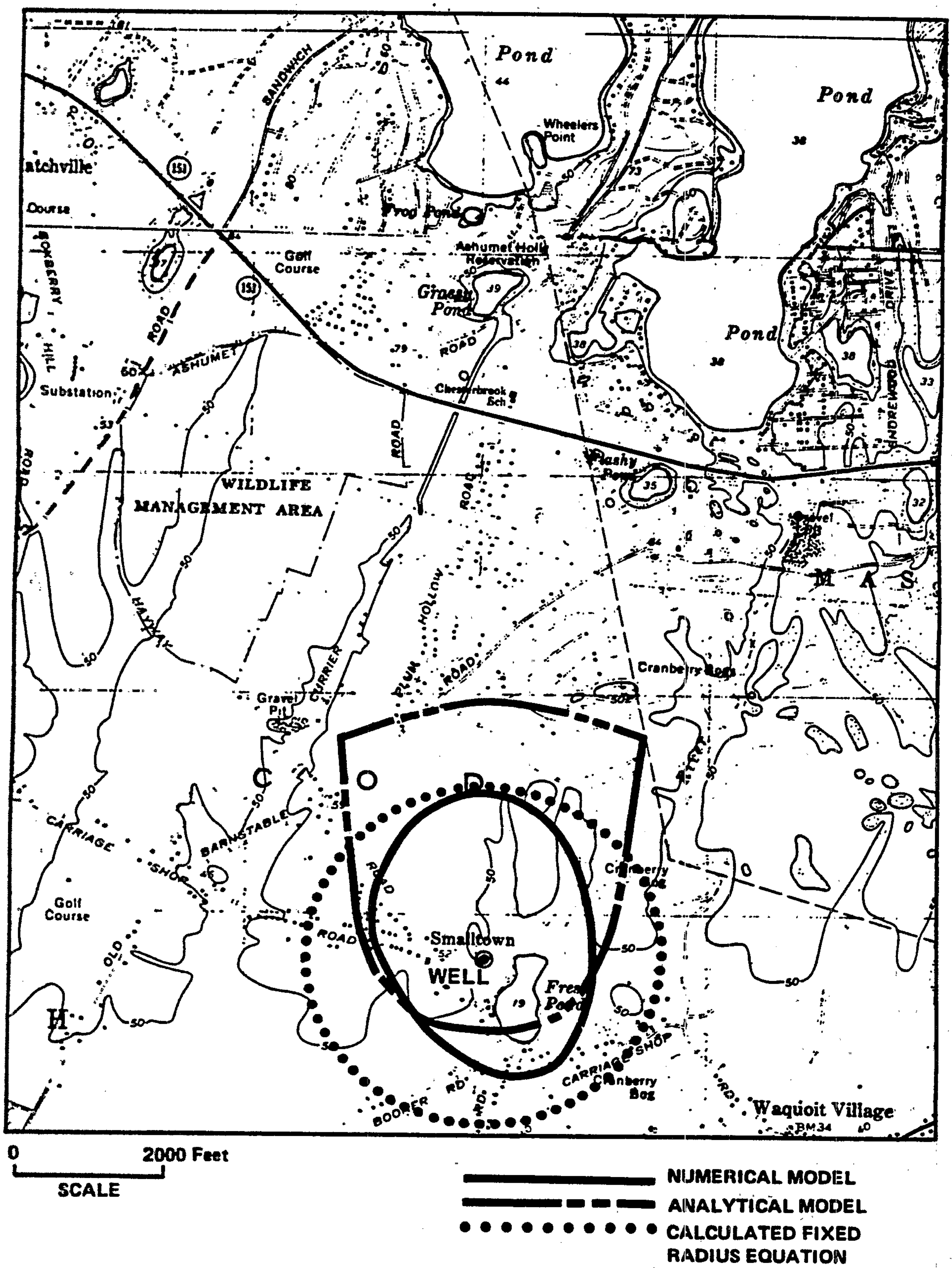


Figure B-6
WHPA Comparative Analysis Example for Well #2 Cape Cod, MA 25-Year TOT

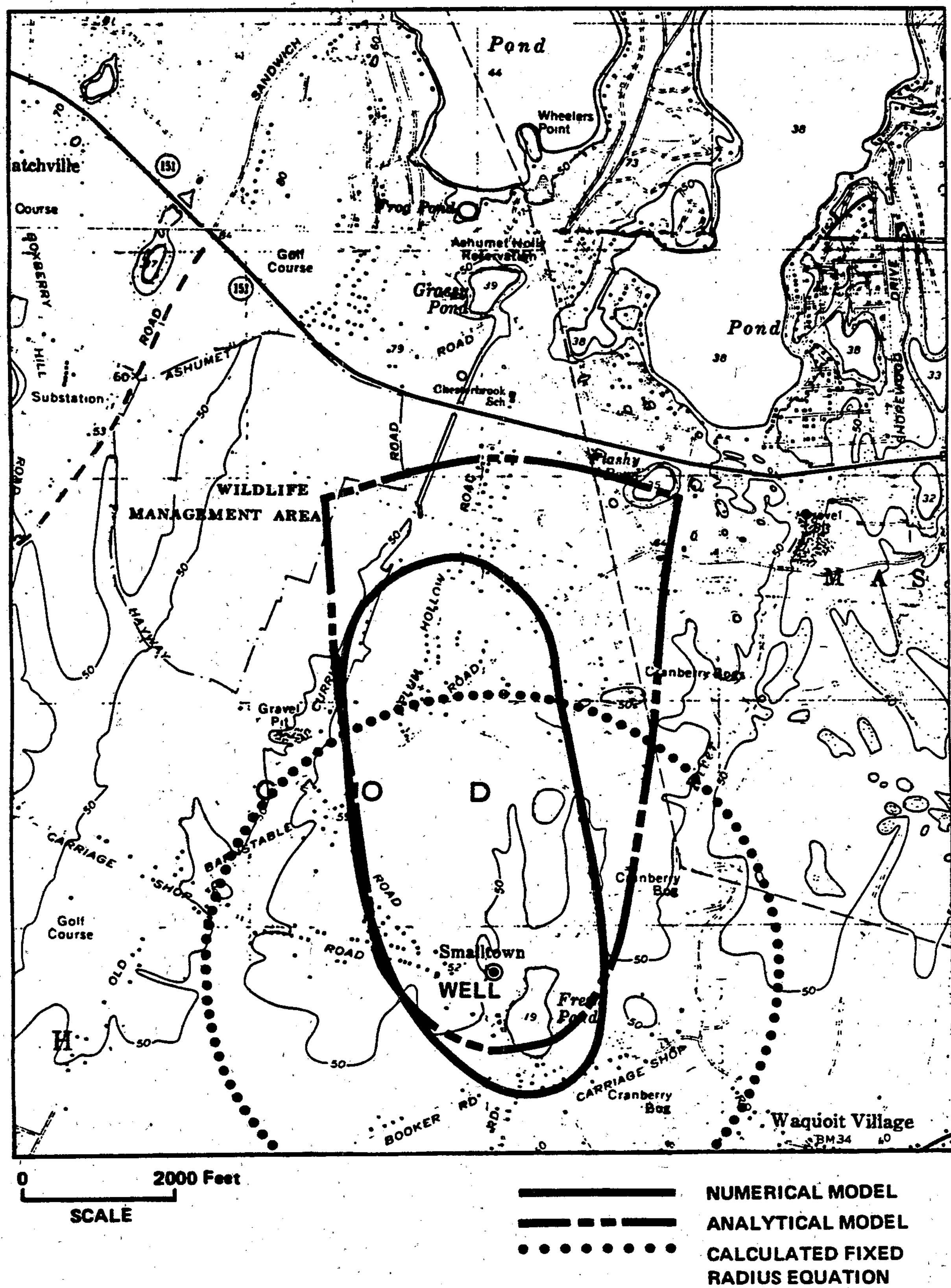
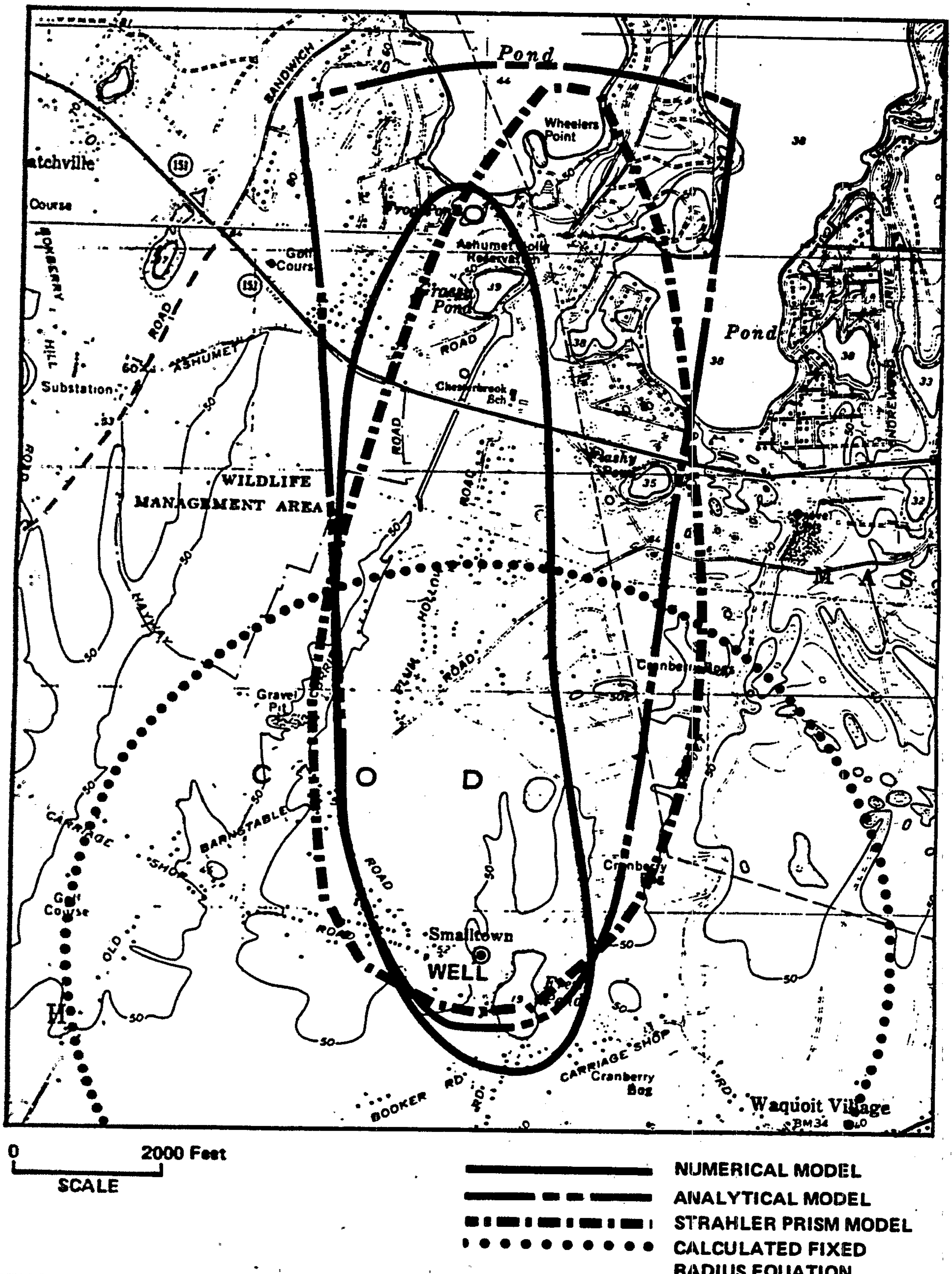


Figure B-7
WHPA Comparative Analysis Example for Well #2 Cape Cod, MA, 50-Year TOT



B.2 SOUTHERN FLORIDA

B.2.1 Hydrogeology of Study Area

Virtually all of southeast Florida's residential, commercial, and industrial water is supplied by hundreds of public and private wells that tap the Biscayne Aquifer. The top of this aquifer lies just 2 to 5 feet beneath the ground surface, and it is recharged by rainfall, streams, canals, and lakes. Approximately 80 to 150 feet deep in place, the aquifer thins along the western boundaries of the study area. The lithology is largely permeable limestones and sandstones. Ground-water flow in the aquifer is primarily horizontal and eastward, toward the sea.

B.2.2 Method Application

Delineation methods used in the Southern Florida comparative analysis were the CFR equation, an analytical model, and a numerical model. The comparison was done for a well field consisting of three wells. WHPA's were delineated for all methods based on TOT criteria thresholds of 30, 210, and 500 days (the County's WHPA criteria).

Calculated Fixed Radius. The CFR equation used was Florida's volumetric equation (see Chapter 4).

Analytical Method. The analytical technique applied was the uniform flow model (Todd, 1980). For modeling purposes, the well field was analyzed as a single well.

Numerical Model. The numerical model used was a three-dimensional finite difference model (McDonald and Harbaugh, 1984) in which WHPA's were delineated based upon drawdown and TOT criteria thresholds (Dames & Moore, 1986).

B.2.3 Data Requirements

Data requirements for each method are listed in Figure B-1. Similar parameters were used as input in each method; they were obtained from a report on the numerical modeling study and are shown in Table B-1. Figure B-1 shows that not all hydrogeologic parameters were used for each method of delineation. The numerical model required the most data and was assumed to provide the most accurate results. In addition, this method was the only method that could take into account the impacts of flow boundaries (such as canals) in the area of WHPA delineation.

B.2.4 Comparison of Resulting WHPA's

The CFR approach provided a moderate overlap with and less coverage than the numerical model for TOT's of 30, 210, and 500 days, as shown in Figures B-8 through B-10. For this well field, no surface-water flow boundary features are located near the well field that affect ground-water flow, although many canals that could have such effects are located in well-field areas in southern Florida. The relatively flat water-table slope in this area is another factor critical to the closer match among methods than in the latter Cape Cod example.

Figure B-8
WHPA Comparative Analysis
Example from Florida, 30-Day TOT

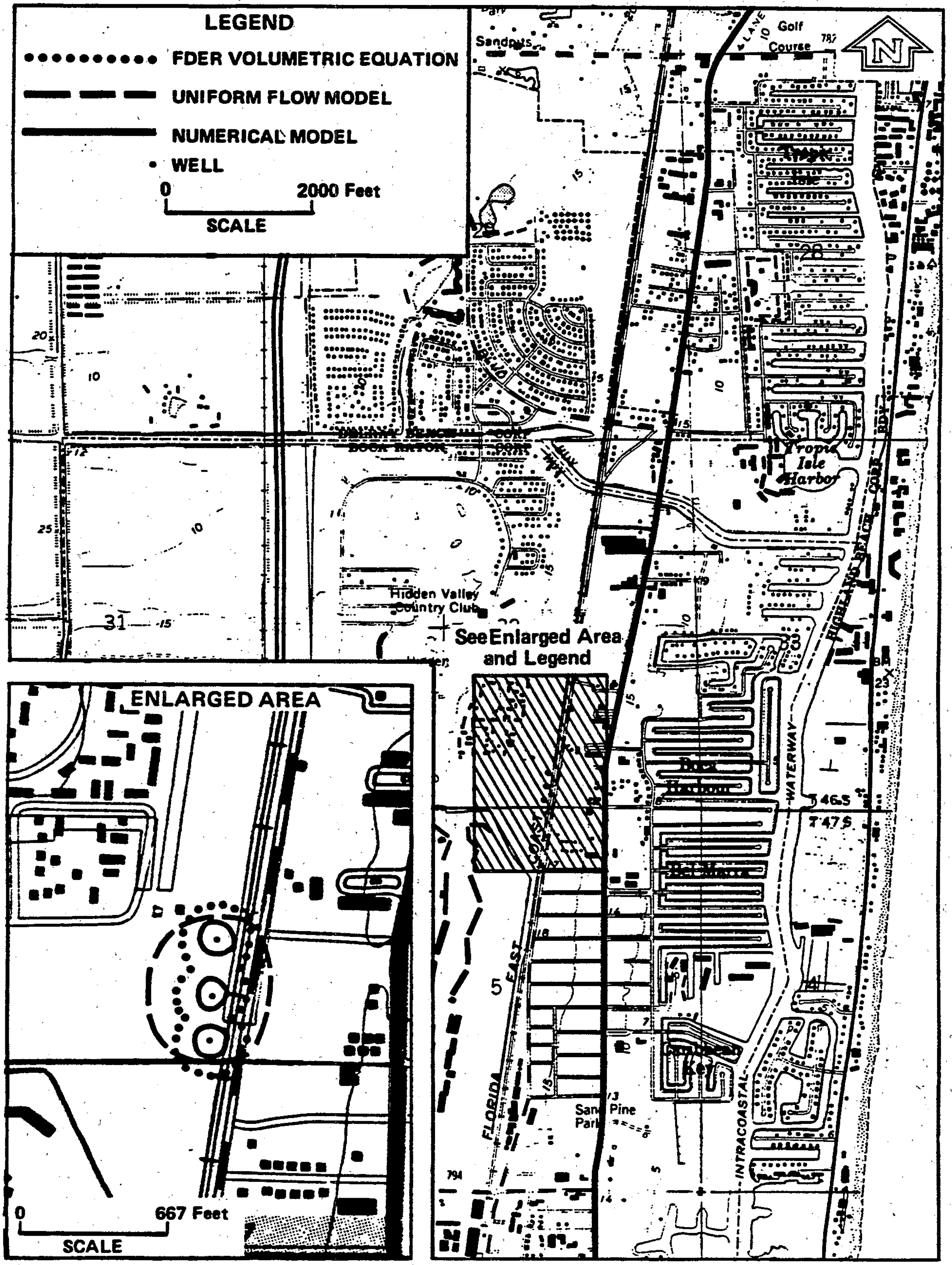


Figure B-9
WHPA Comparative Analysis
Example from Florida, 210-Day TOT

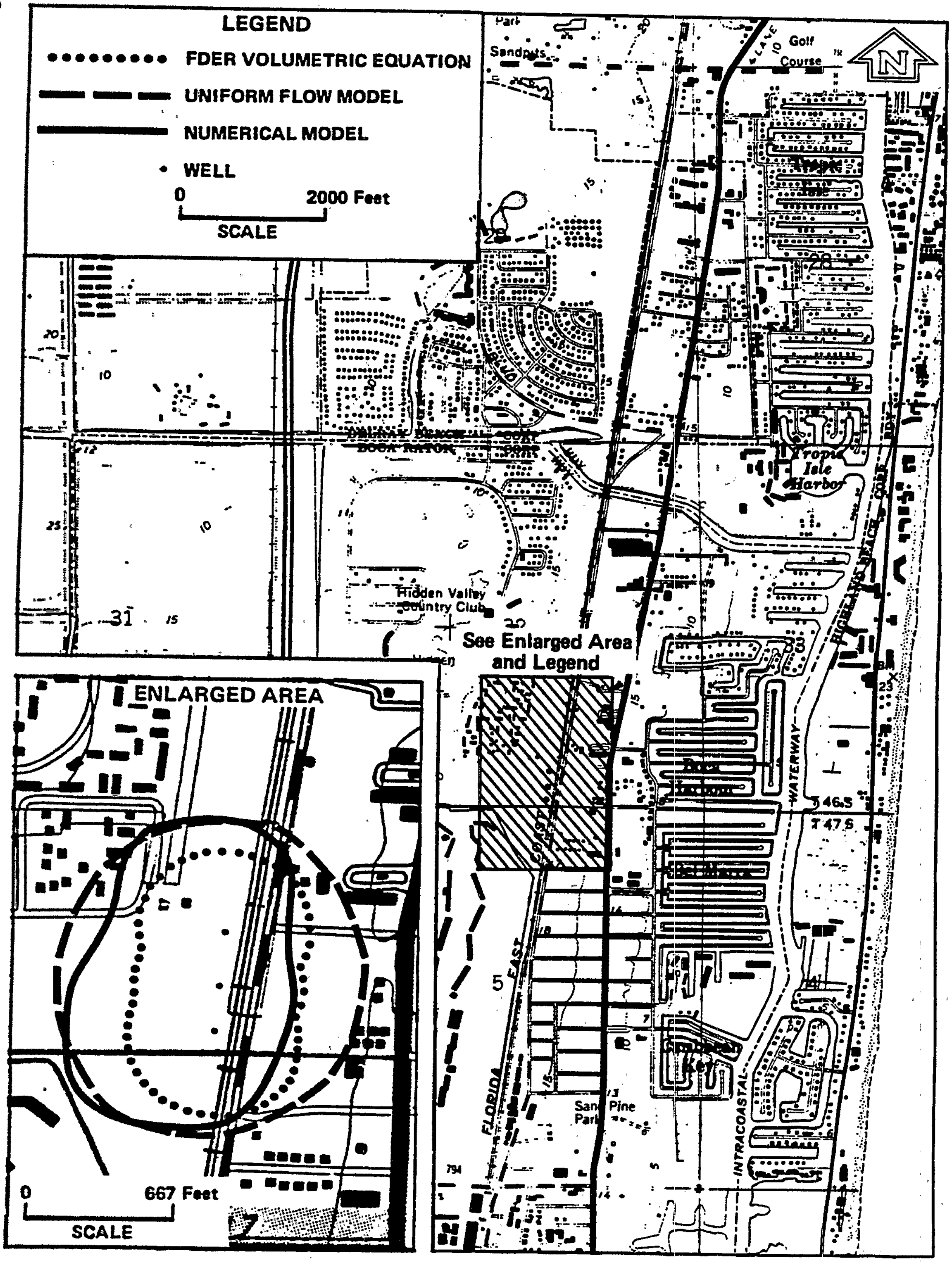
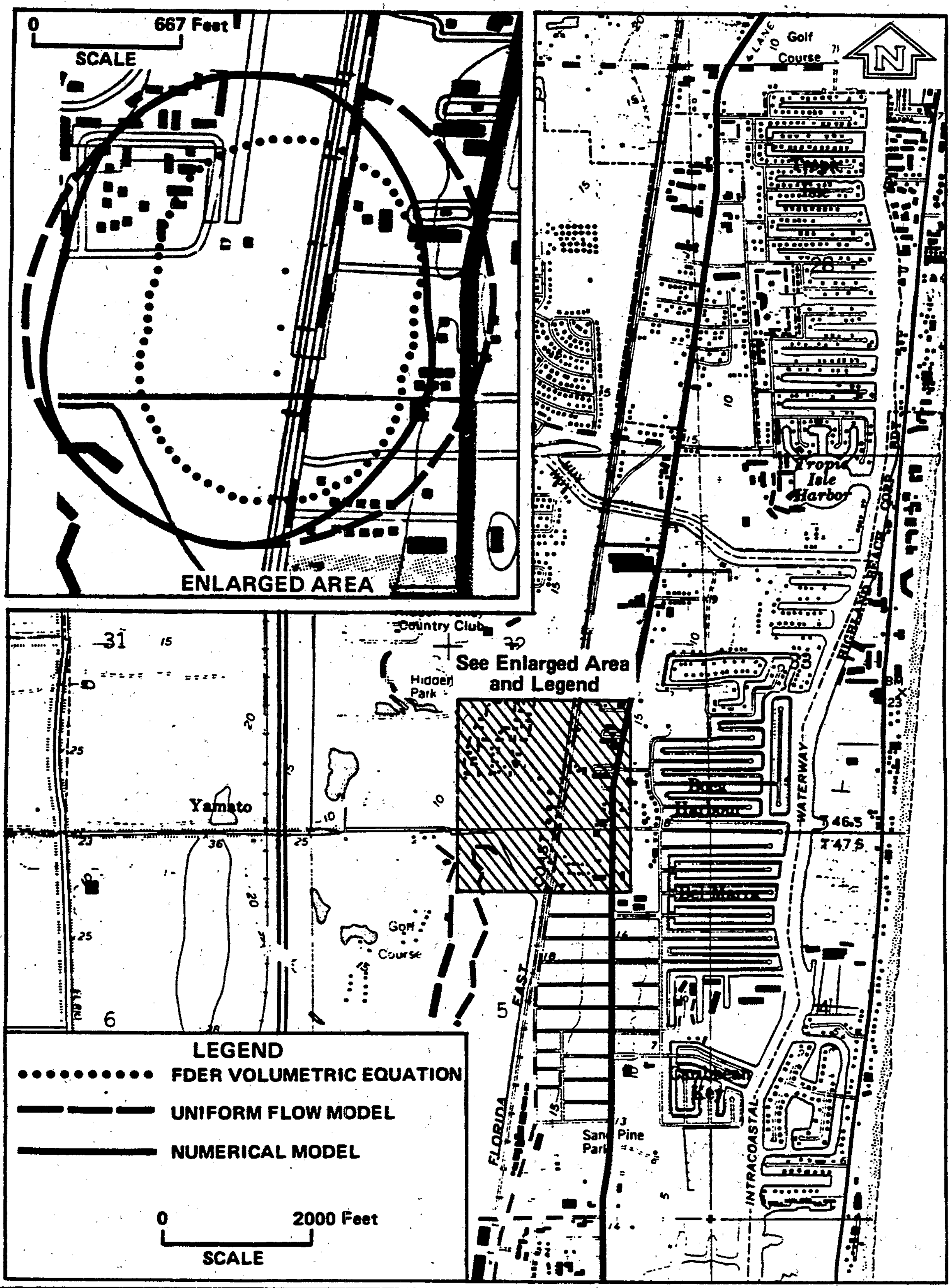


Figure B-10
WHPA Comparative Analysis
Example from Florida, 500-Day TOT



B.3 CENTRAL COLORADO

These comparative analyses for the State of Colorado are based on unpublished information obtained from a joint effort by EPA Region VIII, the Colorado Department of Health, and the U.S. Geological Survey. As part of of this pilot-project effort, WHPA's were delineated based on flow-boundary and travel-time criteria and the application of an analytical method (the uniform flow equations by Todd, 1980) for the purpose of determining zones of contribution to wells used by the Cherokee Water District.

B.3.1 Hydrogeology of Study Area

Currently, the Cherokee Water District withdraws water from the Black Squirrel Aquifer and exports it to suburbs east of Colorado Springs and to the Falcon Air Force Station. The aquifer is located about 25 miles east of Colorado Springs. The setting is largely rural, and the wells are subject to contamination from agricultural sources. The Black Squirrel basin is drained by Black Squirrel Creek and its tributaries. Streams in the area are intermittent, flowing only in response to thunderstorms, snowmelt, and prolonged rainfall. All streams are ephemeral and do not provide dependable sources of water. The basin is underlain by an alluvial aquifer and the four bedrock aquifers of the Denver Basin.

The Black Squirrel Creek aquifer is approximately 100 square miles in extent (at a saturated thickness of at least 60 feet) and receives surface recharge from an area of approximately 350 square miles. Average annual recharge is estimated to be 0.6 to 1.3 inches. Recharge to the alluvial aquifer is about 9,000 acre-feet per year, as infiltration of precipitation and upward leakage from bedrock aquifers. Natural discharge is estimated to be equally divided between evapotranspiration from ground water and ground-water outflow at the downgradient end of the basin.

The source of water to the wells tapping the alluvial aquifer is primarily from aquifer storage. Therefore, ground-water withdrawals have lowered the water table and reduced the discharge to evapotranspiration. Changes in ground-water outflow due to pumping have been small. Changes in leakage from bedrock aquifers are not known, but are assumed to be small. Withdrawals from ground water have been about 11,000 acre-feet per year, 8,000 for agricultural consumption and 3,000 for municipal use. The source of this water has been storage in the alluvial aquifer and salvage of ground water that would have been lost to evapotranspiration. Obtaining accurate knowledge of sources and losses affecting the aquifer is complicated by wells that are unmetered and used seasonally for agricultural irrigation.

B.3.2 Method Application

WHPA delineation methods used in the Colorado comparative analysis included calculated fixed radius and analytical methods. A comparative analysis was done for one well.

Calculated Fixed Radius. The calculated fixed radius (CFR) method used was the Florida volumetric equation (see Chapter 4). WHPA's were delineated for travel times of 1 and 5 years.

Analytical Method. The analytical method applied, the uniform flow model (Todd, 1980), was used to estimate the downgradient and lateral envelope of the WHPA. The upgradient boundaries were determined using 1-, 5-, and 20-year TOT distances determined by the regional ground-water flow velocity, determined from non-pumping water-level maps for the area.

Two approaches were used to apply the uniform flow model. The first approach was described in Chapter 4. In the second approach, the uniform model was applied by the USGS in a slightly different way. The ZOC to the pumping well was assumed to reach its maximum calculated width at the well rather than at some distance upgradient from the well, as assumed with the first approach. Also, a buffer zone was added beyond the calculated ZOC for the well. The buffer zone was computed by doubling the distance from the well to the downgradient null point 2 (X_L) and from the well to the ZOC boundary 2 (Y_L) (Figure 4-7). The buffer zone was extended outward from the calculated ZOC boundary at the well by 50 feet for every 100 feet of distance upgradient from the well.

B.3.3 Data Requirements

Data used in the CFR and analytical methods for the Colorado comparative analysis are listed in Table B-1. The parameters shown in Table B-1 were obtained from USGS studies in the area and parameters reflect conditions around the wells.

B.3.4 Comparison of Resulting WHPA's

Figures B-11 through B-13 show the delineated WHPA's for the well in Colorado using the CFR and the two approaches using the uniform flow model. For the 1-year TOT threshold, the WHPA's delineated using the different methods were relatively similar. For the 5-year TOT, however, there is less similarity among WHPA's delineated using the various methods. Differences are likely due to the fact that the CFR does not incorporate the regional slope of the water table, as the analytical methods do.

For the 20-year TOT distances, only the two approaches used in the analytical methods are compared. The WHPA's delineated with the two methods are relatively similar, though the USGS-delineated WHPA is wider near the well. With the addition of the buffer zone in the USGS approach, however, the resulting WHPA's are substantially larger. Since the effects of the irrigation wells and irrigation flow returns have not been included in this comparative analysis, the addition of a buffer zone to the analytically determined WHPA's appears to be a reasonably conservative approach.

Figure B-11
WHPA Comparative Analysis, Example from Colorado, 1-Year TOT

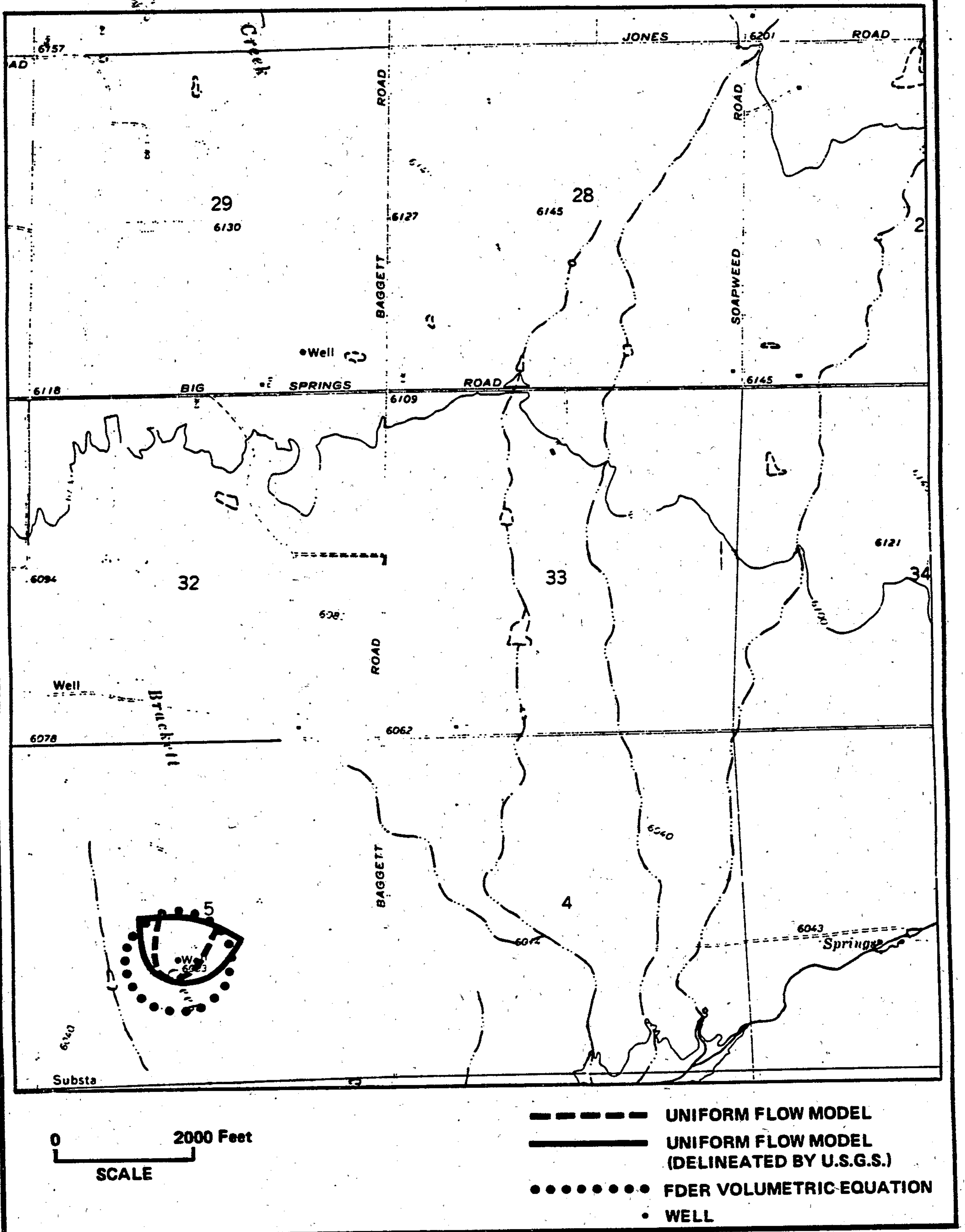
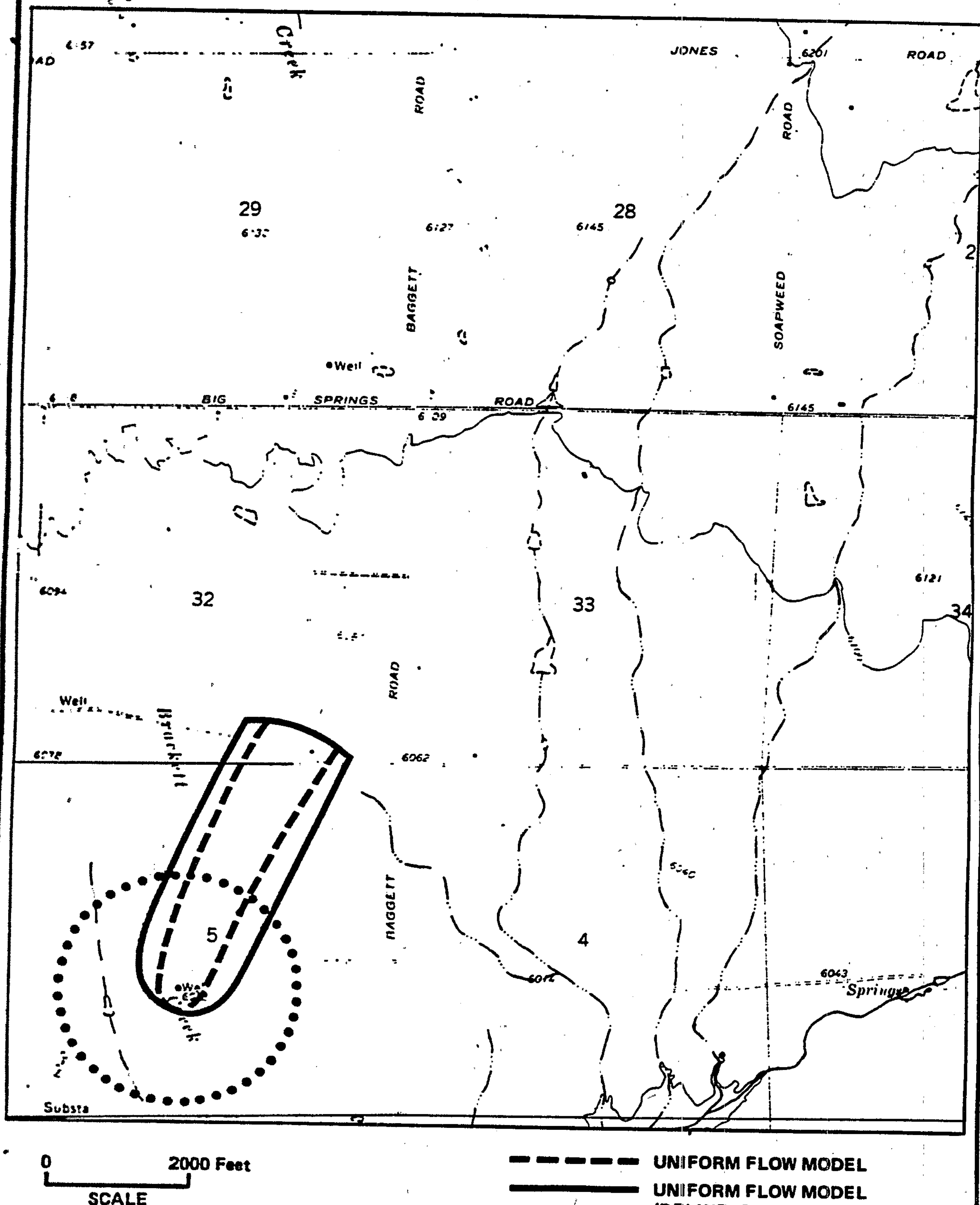
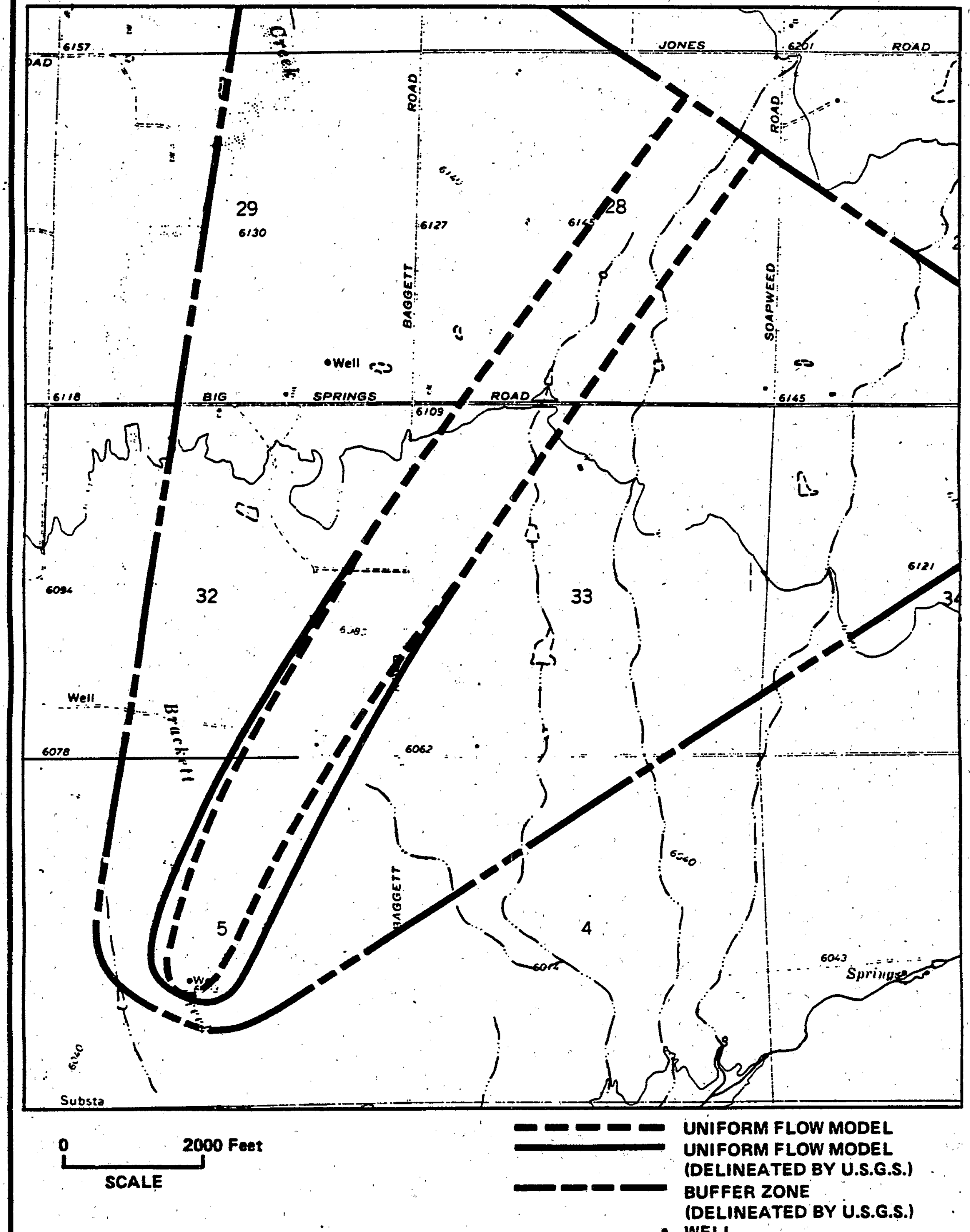


Figure B-12
WHPA Comparative Analysis, Example from Colorado, 5-Year TOT



UNIFORM FLOW MODEL
UNIFORM FLOW MODEL (DELINEATED BY U.S.G.S.)
FDER VOLUMETRIC EQUATION
• WELL

Figure B-13
WHPA Comparative Analysis, Example from Colorado, 20-Year TOT and Buffer Zone



B.4 SOUTHWESTERN CONNECTICUT

In 1985, the Connecticut Department of Environmental Protection, in cooperation with the U.S. Geological Survey, conducted a comprehensive study of the ground-water resources of the Cannondale Aquifer in southwestern Connecticut (Meade and Knowlton, 1985). That study served as the basis and major source of information for the comparative analysis presented in this section. The Cannondale Aquifer is located in the town of Wilton, which is approximately 6 miles north of the city of Norwalk.

B.4.1 Hydrogeology of the Study Area

The Norwalk River basin is very similar, both geologically and hydrologically, to most of the river basins in southwestern Connecticut. The basin is underlain by crystalline bedrock, discontinuously covered by unconsolidated sand and gravel stratified drift deposits. These deposits exhibit a capacity to store and transmit water greater than does the underlying crystalline bedrock. This capacity of the deposits to transmit water, along with their hydraulic connection to the streams flowing through valleys containing the stratified drift deposits, make such stream-valley systems the most prolific type of aquifer for public water supplies in southwestern Connecticut.

The Cannondale Aquifer consists of stratified drift deposits covering a land surface area of approximately 0.32 square mile, with a maximum thickness of 140 feet. Approximately 30 percent (0.15 square mile) of the aquifer has a saturated thickness of less than 10 feet. The Norwalk River runs north-south through the aquifer for a length of about 7,000 feet and a width ranging from 5 to 50 feet.

Precipitation, falling on both the stratified drift deposits and the surrounding till-bedrock uplands, is the major source of water that recharges the stratified drift aquifers. Water derived from both rainfall and snow melt directly on the stratified drift deposits seeps into the ground and percolates through the unsaturated zone where losses to evapotranspiration and soil moisture occur. The remainder of the water reaches the water table and is incorporated into the ground-water flow system. Very little water is lost from the stratified drift deposits as a result of overland runoff.

B.4.2 Method Application

Delineation methods used in the Connecticut comparative analysis were a calculated fixed radius equation, an analytical model, and a numerical model. The comparison was done for a well field consisting of two wells.

Calculated Fixed Radius. The calculated fixed radius method used was the Florida volumetric equation (see Chapter 4). WHPA's were delineated for TOT's of 1 and 5 years.

Analytical Method. The analytical model used to estimate the downgradient and lateral extents of the WHPA was the uniform flow model (Todd, 1980). The upgradient boundaries were determined from a travel-time equation used in England (see Chapter 4). WHPA's were delineated for TOT's of 1 and 5 years. The two wells were treated as a single well in the uniform flow model application.

Numerical Model. The numerical model used was a two-dimensional finite-difference ground-water flow model (Trescott, et al., 1976) applied by the USGS (Meade and Knowlton, 1985). WHPA's were delineated based upon flow boundaries defining the ZOC to a pumping well and drawdown criteria defining the ZOI.

B.4.3 Data Requirements

Parameters used in the Connecticut comparative analysis are shown in Table B-1. The parameters used were obtained from a report on the numerical modeling study (Meade and Knowlton, 1985). In this study, extensive data collection was done to characterize hydrogeologic parameters. Parameters were found to vary throughout the study area and the parameters used in the comparative analysis were those closest to the wells for which the WHPA's were delineated.

B.4.4 Comparison of Resulting WHPA's

Figures B-14 and B-15 show the resulting WHPA's for the two wells in Connecticut delineated with the CFR method, analytical model, and numerical model. For a TOT of 1 year (Figure B-14) results of the CFR and analytical model are relatively similar. However, WHPA's delineated with these methods are smaller than those delineated with the numerical model using flow boundaries and drawdown as criteria.

For the 5-year TOT's, the CFR and analytical model provide greater variation in results. The larger difference is likely due to the effects of regional ground-water gradients. The CFR and analytical model also provide results geometrically different from the numerical model. This is probably because the CFR and analytical models do not account for flow boundaries, such as streams and geologic contacts, that significantly affect ground water flowing to this well field.

Figure B-14
WHPA Comparative Analysis, Example from Connecticut, 1-Year TOT

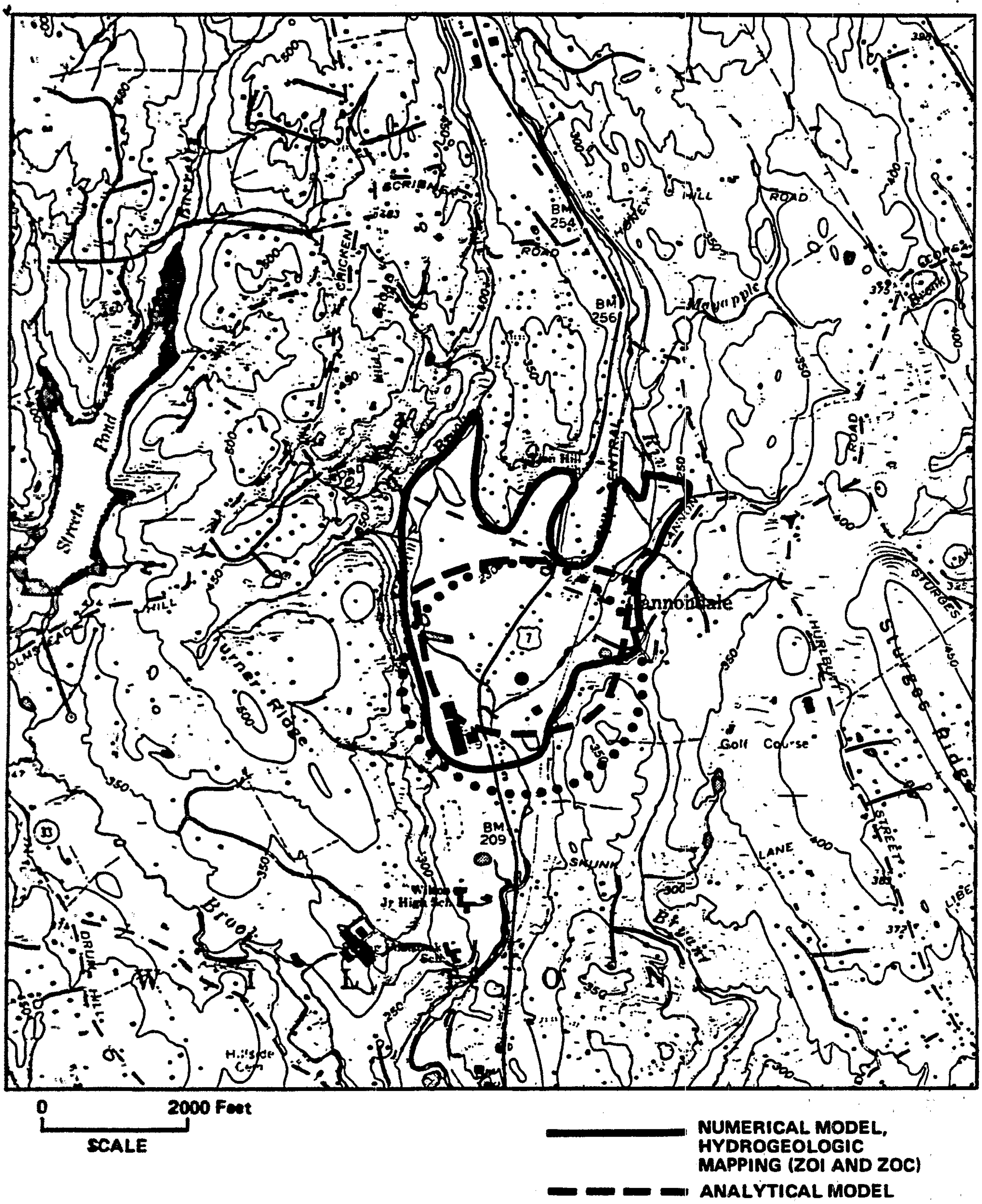
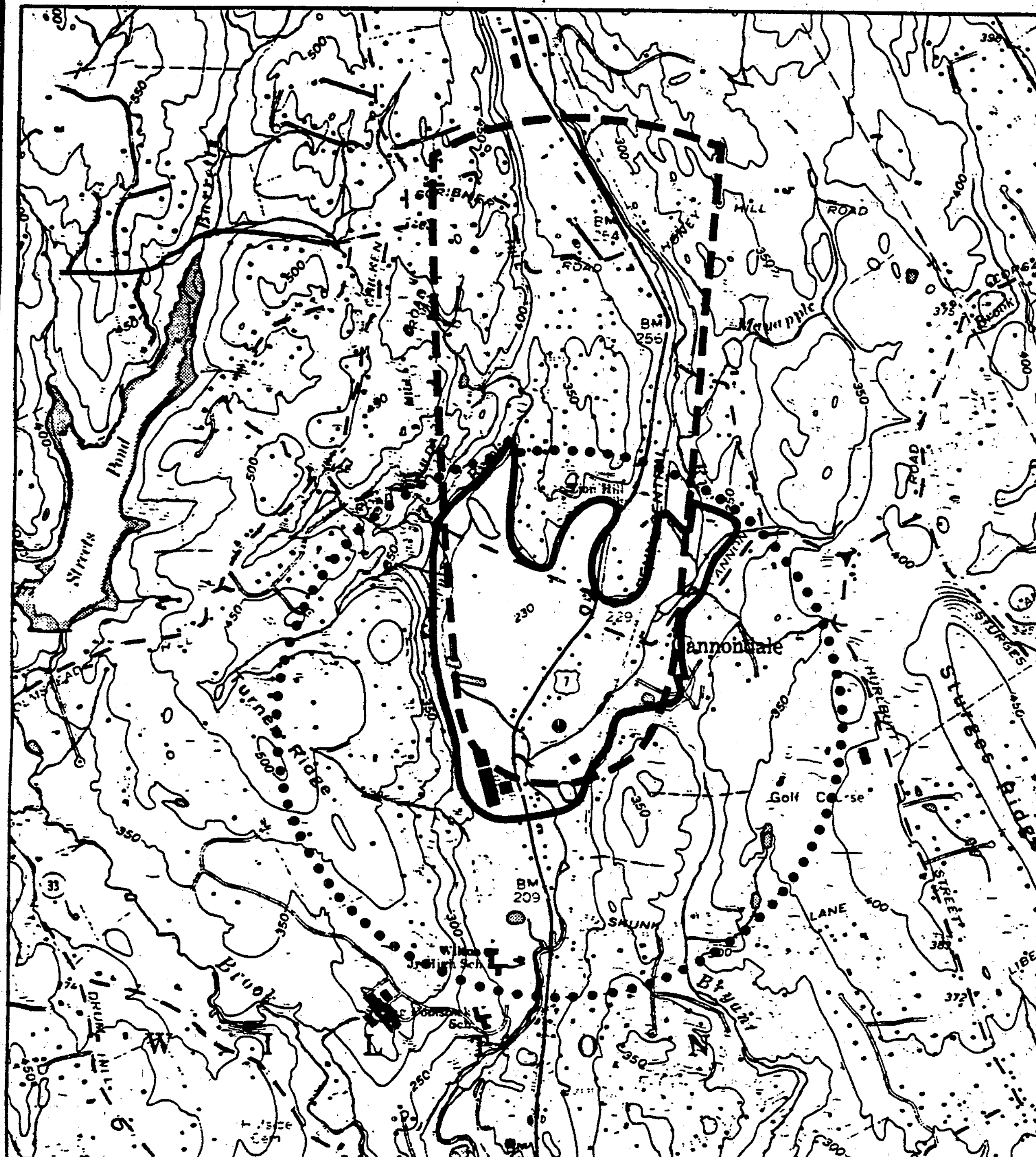


Figure B-15
WHPA Comparative Analysis, Example from Connecticut, 5-Year TOT



0 2000 Feet
SCALE

NUMERICAL MODEL, HYDROGEOLOGIC MAPPING (ZOI AND ZOC)

ANALYTICAL MODEL

CALCULATED FIXED RADIUS EQUATION

B.5 SUMMARY AND CONCLUSION

Different methods can provide significantly different levels of accuracy for WHPA delineation around a well field. This is particularly true if surface water affects ground-water flow or heterogeneous hydrogeologic conditions exist. The process of deciding on a method for delineating WHPA's in an area should include consideration of the validity of the method under existing hydrogeologic conditions in the area (including flow boundaries and gradients), the desired accuracy, and the cost/implementation tradeoffs in moving from relatively simple to more comprehensive methodologies. Comparative analyses have also been shown useful for evaluating criteria and criteria thresholds for consideration in State WHP programs.

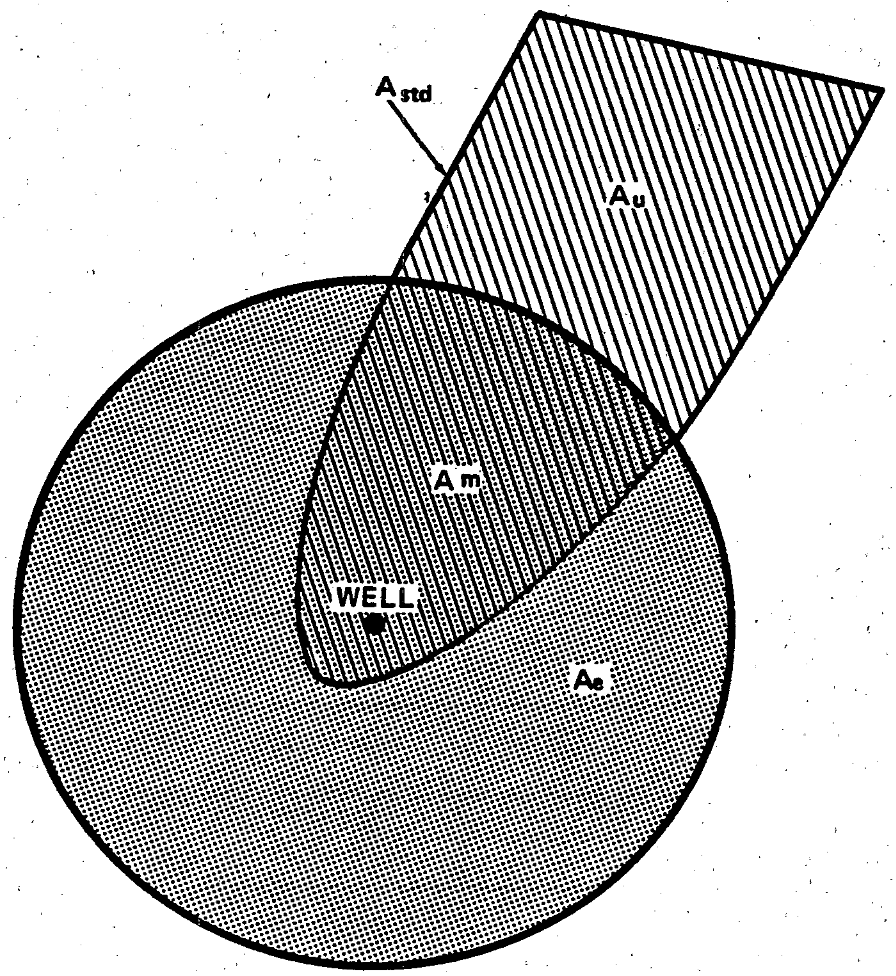
The methodology and nomenclature used to evaluate the comparative analyses are shown in Figure B-16. Table B-2 is a summary of the comparative analyses for the four different localities. The table shows the results of each method and considers the percent of mutual coverage, under-protection relative to the largest area, and erroneous coverage relative to the method considered to be the most accurate. Results are shown for a 5-year TOT for the Connecticut example, a 500-day TOT for the Florida example, and a 50-year TOT for the Cape Cod example. Because WHPA's delineated by numerical modeling were not available as a standard for comparison for the Colorado example, its results are not shown in Table B-2.

For the Connecticut comparative analysis, the CFR model covered the entire numerically delineated WHPA and did not under-protect. However, this method provided considerable erroneous coverage when compared with the numerically delineated WHPA. For this example, the low accuracy was due to the effects of flow boundaries and significant regional ground-water gradients not incorporated in the CFR model.

For the analytical model in the Connecticut example, the method covered nearly all of the numerically delineated WHPA and provided relatively little under-protection. However, as with the CFR model, significant erroneous coverage was due to the effects of flow boundaries.

For the Florida comparative analysis, the WHPA delineated with the CFR model was about half the size of the numerically generated WHPA and no erroneous coverage was provided. The analytically generated WHPA, however, covered all of the numerically generated WHPA and provided only a slight amount of erroneous protection. For this

Figure B-16
Comparative Analysis Nomenclature



Percent mutual coverage = $(A_m/A_{std}) \times 100\%$

Percent under protection = $(A_u/A_{std}) \times 100\%$

Percent erroneous coverage = $\left(\frac{A_e - A_m}{A_{std}}\right) \times 100\%$

WHERE:

A_{std} = Area given by the method used as the standard for comparisons.

A_e = Area given by method to be evaluated.

A_m = Area mutually covered by both methods.

A_u = Area not covered by method being evaluated.

Table B-2
Summary of Results of Comparative Analysis Examples

COMPARATIVE FACTOR \ METHOD	COLORADO[1]			CONNECTICUT[2]			FLORIDA[3]			MASSACHUSETTS[4]		
	CFR	AM	NM	CFR	AM	NM	CFR	AM	NM	CFR	AM	NM
PERCENT MUTUAL COVERAGE	N/A	N/A	N/A	100%	91%	100%	57%	100%	100 %	41%	79%	100%
PERCENT UNDER PROTECTION	N/A	N/A	N/A	0%	9%	0%	43%	0%	0%	59%	21%	0%
PERCENT ERRONEOUS COVERAGE	N/A	N/A	N/A	290%	160%	0%	0%	21%	0%	50%	52%	0%

CFR = Calculated Fixed Radius
AM = Analytical Model
NM = Numerical Model
N/A = Not Applicable

1. Numerical modelling results not available as a standard for comparison
2. Comparison done for 5-Year TOT
3. Comparison done for 500-Day TOT
4. Comparison done for 50-Year TOT for Well No. 1

comparative analysis, the CFR and analytical models provided more accurate protection than in the Connecticut example because water table gradients are lower and flow boundaries are generally absent.

For the Massachusetts comparative analysis, the CFR equation provided a relatively high degree of both under-protection and erroneous coverage. The analytical model, in contrast, provided a high degree of mutual coverage and a small amount of under-protection. However, this method provided a relatively large area of erroneous coverage. The differences in the delineated WHPA's for this comparison were due to the presence of significant regional ground-water gradients and the presence of hydrologic boundaries, including ponds and streams.

APPENDIX C

GLOSSARY

The purpose of this Glossary is to provide a list of terms commonly used by hydrogeologists, as well as some specific terms used in ground-water contamination assessments and wellhead protection. The definitions provided in this glossary are not necessarily endorsed by EPA nor are they to be viewed as suggested language for regulatory purposes. Not all of these terms appear in this document. Numbers in parentheses indicate the reference sources for most of the hydrogeologic terms; the major source was (1). Some adaptations of the definitions in these published references is included.

GLOSSARY REFERENCES

(1) Subsurface-Water Glossary Working Group. 1987. Subsurface-water flow and solute transport--glossary of selected terms. Ground-Water Subcommittee, Interagency Advisory Committee on Water Data. (Unpublished review draft).

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GLOSSARY

Absorption. The process by which substances in gaseous, liquid, or solid form dissolve or mix with other substances (6).

Adsorption. Adherence of ions or molecules in solution to the surface of solids (1). The assimilation of gas, vapor, or dissolved matter by the surface of a solid (2). The attraction and adhesion of a layer of ions from an aqueous solution to the solid mineral surfaces with which it is in contact (3).

Advection. The process whereby solutes are transported by the bulk mass of flowing fluid (1). The process by which solutes are transported by the bulk motion of the flowing ground water (2).

Alluvial. Pertaining to or composed of alluvium or deposited by a stream or running water (2).

Alluvium. A general term for clay, silt, and sand, gravel, or similar unconsolidated material deposited during comparatively recent geologic time by a stream or other body of running water as a sorted or semisorted sediment in the bed of the stream or on its floodplain or delta, or as a cone or fan at the base of a mountain slope (2).

Analytical model. A model that provides approximate or exact solutions to simplified forms of the differential equations for water movement and solute transport. Analytical models can generally be solved with calculations or computers.

Anisotropy. The condition of having different properties in different directions (1). The condition under which one or more of the hydraulic properties of an aquifer vary according to the direction of flow (3).

Anthropogenic. Involving the impact of man on nature; induced or altered by the presence and activities of man.

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield sufficient, economical quantities of water to wells and springs (1,2). Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs (3).

Aquifer system. A body of permeable and relatively impermeable materials that functions regionally as a water-yielding unit. It comprises two or more permeable units separated at least locally by confining units that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system. The permeable materials can include both saturated and unsaturated sections (1).

Aquifer test. A test to determine hydrologic properties of an aquifer, involving the withdrawal of measured quantities of water from, or addition of water to, a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition (1,2).

Area of influence. Area surrounding a pumping or recharging well within which the water table or potentiometric surface has been changed due to the well's pumping or recharge (1).

Artesian. Commonly used expression, generally synonymous with (but less favored term than) "confined."

Artesian aquifer. Commonly used expression, generally synonymous with (but less favored term than) "confined aquifer."

Artesian well. A well deriving its water from a confined aquifer (2).

Attenuation. The process of diminishing contaminant concentrations in ground water, due to filtration, biodegradation, dilution, sorption, volatilization, and other processes.

Base flow. That part of stream discharge not attributable to direct runoff from precipitation or snowmelt, usually sustained by ground-water discharge (1). That part of a stream discharge derived from ground water seeping into the stream (3).

Bedrock. A general term for the rock, usually solid, that underlies soil or other unconsolidated material (2).

Bernoulli's Equation. Under conditions of steady flow of water, the sum of the velocity head, the pressure head, and the head due to elevation at any given point is equal to the sum of these heads at any other point plus or minus the head losses between the points due to friction or other causes (4).

Breakthrough curve. A plot of relative concentration versus time, where relative concentration is defined as C/C_0; the concentration at a point in the ground-water flow domain divided by the source concentration.

Calibration. Adjustment of the input data until computed heads match the field values.

CAPA. See Critical Aquifer Protection Area.

Capillary action. The movement of water within the interstices of a porous medium due to the forces of adhesion, cohesion, and surface tension acting in a liquid that is in contact with a solid. Synonymous with capillarity, capillary flow, and capillary migration (1).

Capillary fringe. The zone at the bottom of the vadose zone where ground water is drawn upward by capillary force (2). The zone immediately above the water table, where water is drawn upward by capillary action (3).

Capillary rise. The height above a free water surface to which water will rise by capillary action (1).

Capillary water. Water held in the soil above the phreatic surface by capillary forces; or soil water above hydroscopic moisture and below the field capacity (1).

Carbonate. A sediment formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron (2).

Carbonate rocks. A rock consisting chiefly of carbonate minerals, such as limestone and dolomite (2).

Clastic. Pertaining to a rock or sediment composed principally of broken fragments that are derived from pre-existing rocks or minerals and that have been transported some distance from their places of origin (2).

Coefficient of storage. The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (2).

Coefficient of transmissivity. See transmissivity (2).

Colloid. Extremely small solid particles, 0.0001 to 1 micron in size, which will not settle out of a solution; intermediate between a true dissolved particle and a suspended solid, which will settle out of solution (2).

Cone of depression (COD). A depression in the ground-water table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines (in cross-section) the area of influence of a well. Also called pumping cone and cone of drawdown (COD) (1,2).

Confined aquifer. An aquifer bounded above and below by confining units of distinctly lower permeability than the aquifer media; or one containing confined ground water (1). An aquifer in which ground water is under pressure significantly greater than atmospheric and its upper limit is the bottom of a bed of distinctly lower hyraulic conductivity than that of the aquifer itself.

Confining unit. A hydrogeologic unit of relatively impermeable material, bounding one or more aquifers. This is a general term that has replaced aquitard, aquifuge, and aquiclude and is synonymous with confining bed (1). A body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may lie above or below the aquifer (3).

Connate water. Ground water entrapped in the interstices of a sedimentary or extrusive igneous rock at the time of its deposition (1).

Consolidated aquifer. An aquifer made up of consolidated rock that has undergone solidification or lithification.

Contaminant. An undesirable substance not normally present, or an usually high concentration of a naturally occurring substance, in water, soil, or other environmental medium (1).

Contamination. The degradation of natural water quality as a result of man's activities. There is no implication of any specific limits, since the degree of permissible contamination depends upon the intended end use, or uses, of the water (2).

Convective transport. The component of movement of heat or mass induced by thermal gradients in ground water (see advection).

Criteria, WHPA. Conceptual standards that form the basis for WHPA delineation. WHPA criteria can include distance, drawdown, time of travel, assimilative capacity, and flow boundaries.

Critical Aquifer Protection Area (CAPA). As defined in the Safe Drinking Water Act, is (1) all or part of an area located within an area for which an application of designation as a sole or principal source aquifer (pursuant to Section 1424(e)) has been submitted and approved by the Administrator not later than 24 months after the date of enactment and which satisfies the criteria established by the Administrator; and (2) all or part of an area that is within an aquifer designated as a sole source aquifer (SSA), as of the date of enactment of the Safe Drinking Water Act Amendments of 1986, and for which an areawide ground-water protection plan has been approved under Section 208 of the Clean Water Act prior to such enactment.

Darcy's law. An empirically derived equation for the flow of fluids through porous media. It is based on the assumptions that flow is laminar and inertia can be neglected, and states that velocity of flow is directly proportional to hydraulic gradient (see specific discharge).

Delay time. Duration of time for contaminant or water to move from point of concern to the well; analogous to time-of-travel.

Density. Matter measured as mass per unit volume expressed in pounds per gallon (lb/gal), pounds per cubic foot (lb/ft^3), and kilograms per cubic meter (kg/m^3) (2). The mass of quantity of a substance per unit volume. Units are kilograms per cubic meter or grams per cubic centimeter (3).

Desorption. See sorption, which is the reverse process.

Diffusion coefficient. See molecular diffusion.

Diffusivity, soil water. The hydraulic conductivity divided by the differential water capacity, or the flux of water per unit gradient of moisture content in the absence of other force fields (1).

Direct precipitation. Water that falls directly into a lake or stream without passing through any land phase of the runoff cycle (3).

Discharge area. An area in which ground water is discharged to the land surface, surface water, or atmosphere (1). An area in which there are upward components of hydraulic head in the aquifer. Ground water is flowing toward the surface in a discharge area and may escape as a spring, seep, or base flow, or by evaporation and transpiration (3).

Discharge velocity. An apparent velocity, calculated by Darcy's law, which represents the flow rate at which water would move through an aquifer if the aquifer were an open conduit. Also called specific discharge (3).

Dispersion. The spreading and mixing of chemical constituents in ground water caused by diffusion and mixing due to microscopic variations in velocities within and between pores (2).

Dispersion coefficient. A measure of the spreading of a flowing substance due to the nature of the porous medium (and specific substance or fluid properties), with interconnected channels distributed at random in all directions. Also the sum of the coefficients of mechanical dispersion and molecular diffusion in a porous medium (1).

Dispersivity. A property of a porous medium (and the specific substance or fluid) that determines the dispersion characteristics of the contaminant in that medium by relating the components of pore velocity to the dispersion coefficient (1).

Distribution coefficient. The quantity of a solute sorbed per unit weight of a solid divided by the quantity dissolved in water per unit volume of water (1).

Drainage basin. The land area from which surface runoff drains into a stream system (3).

Drawdown. The vertical distance ground-water elevation is lowered, or the amount pressure head is reduced, due to the removal of ground water. Also the decline in potentiometric surface caused by the withdrawal of water from a hydrogeologic unit (1). The distance between the static water level and the surface of the cone of depression (2). A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of ground water from wells (3).

Dynamic equilibrium. A condition of which the amount of recharge to an aquifer equals the amount of natural discharge (3).

Effective porosity. The amount of interconnected pore space through which fluids can pass, expressed as a percent of bulk volume. Part of the total porosity will be occupied by static fluid being held to the mineral surface by surface tension, so effective porosity will be less than total porosity (3).

Effluent stream. See gaining stream.

Equipotential line. Surface (or line) along which the potential is constant (1). A contour line on the water table or potentiometric surface; a line along which the pressure head of ground water in an aquifer is the same. Fluid flow is normal to these lines in the direction of decreasing fluid potential (2). A line in a two-dimensional ground-water flow field such that the total hydraulic head is the same for all points along the line (3).

Equipotential surface (line). A surface (or line) in a three-dimensional ground-water flow field such that the total hydraulic head is the same everywhere on the surface (3).

Evapotranspiration. Combined loss of water from a land area, during a specified period of time, through evaporation from the soil and transpiration of plants (2). The sum of evaporation plus transpiration (3).

Evapotranspiration, actual. The evaporation that actually occurs under given climatic and soil-moisture conditions (3).

Evapotranspiration, potential. The evapotranspiration that would occur under given climatic conditions if there were unlimited soil moisture (3).

Exchange capacity. Amount of exchangeable ions, measured in milliequivalents per 100 grams of solid material at a given pH. The total ionic charge of the adsorption complex active in the adsorption of ions (see cation exchange) (1).

Fissure. A surface of a fracture or crack in a rock along which there is a distinct separation (4).

Flow line. The general path that a particle of water follows under laminar flow conditions (1). Line indicating the direction followed by ground water toward points of discharge. Flow lines are perpendicular to equipotential lines (2).

Flow model. A digital computer model that calculates a hydraulic head field for the modeling domain using numerical methods to arrive at an approximate solution to the differential equation of ground-water flow.

Flow net. A graphical representation of flow lines and equipotential lines for two-dimensional, steady-state ground-water flow (1).

Flow path. Subsurface course a water molecule or solute would follow in a given ground-water velocity field (1).

Flow, steady. A characteristic of a flow system, where the magnitude and direction of specific discharge are constant in time at any point (1).

Flow, uniform. A characteristic of a flow system where specific discharge has the same magnitude and direction at any point (1).

Flow, unsteady (nonsteady). A characteristic of a flow system where the magnitude and/or direction of the specific discharge changes with time (1).

Flow velocity. See specific discharge.

Fluid potential. Mechanical energy per unit mass of a fluid at any given point in space and time, with regard to an arbitrary state and datum (1).

Flux. See specific discharge.

Formation. A body of rock of considerable thickness that has characteristics making it distinguishable from adjacent rock unit.

Fracture. A general term for any breakin a rock, which includes cracks, joints and faults (4).

Gaining stream. A stream or reach of a stream, the flow of which is being increased by inflow of ground water. Also known as an effluent stream (3).

Glacial drift. A general term for unconsolidated sediment transported by glaciers and deposited directly on land or in the sea (2).

GPD. Gallons per day, a measure of the withdrawal rate of a well.

Gravitational head. Component of total hydraulic head related to the position of a given mass of water relative to an arbitrary datum (1).

Gravitational water. Water that moves into, through, or out of a soil or rock mass under the influence of gravity (1).

Ground water. That part of the subsurface water that is in the saturated zone (1). The water contained in interconnected pores located below the water table in an unconfined aquifer or located in a confined aquifer (3).

Ground-water barrier. Rock or artificial material with a relatively low permeability that occurs (or is placed) below ground surface, where it impedes the movement of ground water and thus causes a pronounced difference in the heads on opposite sides of the barrier (1).

Ground-water basin. General term used to define a ground-water flow system that has defined boundaries and may include more than one aquifer underlain by permeable materials that are capable of storing or furnishing a significant water supply. The basin includes both the surface area and the permeable materials beneath it (1). A rather vague designation pertaining to a ground-water reservoir that is more or less separate from neighboring ground-water reservoirs. A ground-water basin could be separated from adjacent basins by geologic boundaries or by hydrologic boundaries (3).

Ground water, confined. Ground water within an aquifer that underlies a confining unit.

Ground-water discharge. Flow of water released from the zone of saturation (1).

Ground-water divide. Ridge in the water table, or potentiometric surface, from which ground water moves away at right angles in both directions (1). Line of highest hydraulic head in the water table or potentiometric surface.

Ground-water flow. The movement of water through openings in sediment and rock that occurs in the zone of saturation (1).

Ground-water model. A simplified conceptual or mathematical image of a ground-water system, describing the feature essential to the purpose for which the model was developed and including various assumptions pertinent to the system. Mathematical ground-water models can include numerical and analytical models.

Ground-water mound. Raised area in a water table or other potentiometric surface, created by ground-water recharge.

Ground-water recharge. Process of water addition to the saturated zone, or the volume of water added by this process (1).

Head, static. The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. The static head is the sum of the elevation head and the pressure head (1).

Head, total. The sum of the elevation head (distance of a point above datum), the pressure head (the height of a column of liquid that can be supported by static pressure at the point), and the velocity head (the height to which the liquid can be raised by its kinetic energy) (1). See also hydraulic head.

Heterogeneity. Characteristic of a medium in which material properties vary from point to point (1).

Homegeneity. Characteristic of a medium in which material properties are identical throughout (1).

Hydraulic barrier. Modifications to a ground-water flow system that restrict or impede movement of contaminants (1).

Hydraulic conductivity (K). Proportionality constant relating hydraulic gradient to specific discharge, which for an isotropic medium and homogeneous fluid, equals the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (1). The rate of flow of water in gallons per day through a cross section of one square foot under a unit hydraulic gradient, at the prevailing temperature (gpd/ft^2). In the Standard International System, the units are m^3/day/m^2 or m/day (2). A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity (2).

Hydraulic conductivity, effective. Rate of water flow through a porous medium that contains more than one fluid (such as water and air in the unsaturated zone), which should be specified in terms of both the fluid type and content and the existing pressure (1).

Hydraulic gradient (i). Slope of a water table or potentiometric surface. More specifically, change in static head per unit of distance in a given direction, generally the direction of the maximum rate of decrease in head (1). The rate of change in total head per unit of distance of flow in a given direction (2). The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head (3). The difference in hydraulic heads ($h_1 - h_2$), divided by the distance (L) along the flowpath.

$$i = (h_1 - h_2) / L$$

Hydraulic head. Height above a datum plane (such as mean sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a ground-water system. Equal to the distance between the water level in a well and the datum plane (1).

Hydrodynamic dispersion. Spreading (at the macroscopic level) of the solute front during transport resulting from both mechanical dispersion and molecular diffusion (1). The process by which ground water containing a solute is diluted with uncontaminated ground water as it moves through an aquifer (see dispersion coefficient) (3).

Hydrogeologic. Those factors that deal with subsurface waters and related geologic aspects of surface waters (2).

Hydrogeologic parameters. Numerical parameters that describe the hydrogeologic characteristics of an aquifer such as porosity, permeability, and transmissivity.

Hydrogeologic unit. Any soil or rock unit or zone that because of its hydraulic properties has a distinct influence on the storage or movement of ground water (1).

Hydrostatic pressure. Pressure exerted by the weight of water at any given point in a body of water at rest (1).

Immiscible. The chemical property where two or more liquids or phases do not readily dissolve in one another, such as oil and water (1).

Impermeability. Characteristic of geologic materials that limit their ability to transmit significant quantities of water under the pressure differences normally found in the subsurface environment (1).

Infiltration. The downward entry of water into soil or rock (1).

Infiltration rate. Rate at which soil or rock under specified conditions absorbs falling rain, melting snow, or surface water; expressed in depth of water per unit time. Also, the maximum rate at which water can enter soil or rock under specified conditions, including the presence of an excess of water; expressed in units of velocity (1).

Influent stream. See losing stream.

Interference. The result of two or more pumping wells, the drawdown cones of which intercept. At a given location, the total well interference is the sum of the drawdowns due to each individual well (3). The condition occurring when the area of influence of a water well comes into contact with or overlaps that of a neighboring well, as when two wells are pumping from the same aquifer or are located near each other (2).

Interstice. An opening or space in rock or soil that may be occupied by air, water, or other fluid; synonymous with void or pore (1).

Intrinsic permeability. Pertaining to the relative ease with which a porous medium can transmit a liquid under a hydraulic or potential gradient. It is a property of the porous medium and is independent of the nature of the liquid or the potential field (3).

Ion. Any element or compound that has gained or lost an electron, so that it is no longer neutral electrically, but carries a charge (2).

Isochrone. Plotted line graphically connecting all points having the same time of travel for contaminants to move through the saturated zone and reach a well.

Isoconcentration. Graphic plot of points having the same contaminant concentration levels.

Isotropy. The condition in which the properties of interest (generally hydraulic properties of the aquifer) are the same in all directions (1).

Karst topography. A type of terrain that is formed on limestone, gypsum, and other rocks by dissolution, and is characterized by sinkholes, caves, and underground drainage (1).

Kinematic viscosity. The ratio of dynamic viscosity to mass density. It is obtained by dividing dynamic viscosity by the fluid density. Units of kinematic viscosity are square meters per second (2).

Laminar flow. Fluid flow in which the head loss is proportional to the first power of the velocity; synonymous with streamline flow and viscous flow. The stream lines remain distinct and the flow directions at every point remain unchanged with time. It is characteristic of the movement of ground water (1). Type of flow in which the fluid particles follow paths that are smooth, straight, and parallel to the channel walls. In laminar flow, the viscosity of the fluid damps out turbulent motion. Compare with turbulent flow (2).

Leaching. Removal of materials in solution from rock, soil, or waste; separation or dissolving out of soluble constituents from a porous medium by percolation of water (1).

Leakage. Flow of water from one hydrogeologic unit to another. This may be natural, as through a somewhat permeable confining layer, or anthropogenic, as through an uncased well. It may also be the natural loss of water from artificial structures, as a result of hydrostatic pressure (1).

Leaky aquifer. An artesian or water table aquifer that loses or gains water through adjacent semipermeable confining units (1).

Limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite (1).

Losing stream. A stream or reach of a stream that is losing water by seepage into the ground. Also known as an influent stream (3).

Matrix. Solid framework of a porous material or system (1).

Maximum Contaminant Level (MCL). Maximum permissible level of a contaminant in water that is delivered to the users of a public water system. MCL is defined more explicitly in SDWA regulations (40 CFR Section 141.2).

MCL. See Maximum Contaminant Level.

Mechanical dispersion. Process whereby solutes are mechanically mixed during advective transport, caused by the velocity variations at the microscopic level; synonymous with hydraulic dispersion (1). The coefficient of mechanical dispersion is the component of mass transport flux of solutes caused by velocity variations at the microscopic level (1).

MGD. Million gallons per day, a measure of the withdrawal rate of a well.

Miscible. Chemical characteristic of two or more liquids or phases, making them able to mix and dissolve in each other, or form one phase (1).

Miscible displacement. Mutual mixing and movement of two fluids that are soluble in each other; synonymous with miscible-phase displacement (1).

Molecular diffusion. Process in which solutes are transported at the microscopic level due to variations in the solute concentrations within the fluid phases (1). Dispersion of a chemical caused by the kinetic activity of the ionic or molecular constituents (2).

Nonpoint source. A source discharging pollutants into the environment that is not a single point (1).

Observation well. A well drilled in a selected location for the purpose of observing parameters such as water levels and pressure changes (2). A nonpumping well used to observe the elevation of the water table or the potentiometric surface. An observation well is generally of larger diameter than a piezometer and typically is screened or slotted throughout the thickness of the aquifer (3).

Parameter. See hydrogeologic parameter.

Partial penetration. When the intake portion of the well is less than the full thickness of the aquifer (2). A well constructed in such a way that it draws water directly from a fractional part of the total thickness of the aquifer. The fractional part may be located at the top, the bottom, or anywhere else in the aquifer (3).

Particulate transport. Movement of undissolved particles in subsurface water (1).

Peclet number. Relationship between the advective and diffusive components of solute transport; expressed as the ratio of the product of the average interstitial velocity and the characteristic length, divided by the coefficient of molecular diffusion. Small values indicate diffusion dominates; large values indicate advection dominates (1).

Perched water. Unconfined ground water separated from an underlying main body of ground water by an unsaturated zone (2).

Percolation. Downward movement of water through the unsaturated zone; also defined as the downward flow of water in saturated or nearly saturated porous media at hydraulic gradients of 1.0 or less (1). The act of water seeping or filtering through the soil without a definite channel (2).

Permeability. Ability of a porous medium to transmit fluids under a hydraulic gradient (1). The property or capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure (2).

Permeability coefficient. Rate of flow of water through a unit cross-sectional area under a unit hydraulic gradient at the prevailing temperature (field permeability coefficient), or adjusted to 15 degrees C (1).

Permeability, effective. Observed permeability of a porous medium to one fluid phase, under conditions of physical interaction between the phase and other fluid phases present (1).

Permeability, intrinsic. Relative ease with which porous medium can transmit a fluid under a potential gradient, as a property of the medium itself. Property of a medium expressing the relative ease with which fluids can pass through it (1).

pH. A measure of the acidity or alkalinity of a solution, numerically equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with increasing acidity. Originally stood for "potential of hydrogen" (2).

Phreatic water. See saturated zone.

Piezometric surface. See potentiometric surface.

Point source. Any discernible, confined, or discrete conveyance from which pollutants are or may be discharged, including (but not limited to) pipes, ditches, channels, tunnels, conduits, wells, containers, rolling stock, concentrated animal feeding operations, or vessels (1).

Pollutant. Any solute or cause of change in physical properties that renders water unfit for a given use (3).

Pollution. When the contamination concentration levels restrict the potential use of ground water (2).

Pore. See interstice.

Pore space. Total space in an aquifer medium not occupied by solid soil or rock particles (1).

Porosity (n). Ratio of the total volume of voids available for fluid transmission to the total volume of a porous medium. Also the ratio of the volume of the voids of a soil or rock mass that can be drained by gravity to the total volume of the mass (1). The percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected (2). The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment (3). Porosity may be primary, formed during deposition or cementation of the material, or secondary, formed after deposition or cementation, such as fractures.

Potable water. Suitable for human consumption as drinking water (1).

Potential. Any of several scalar variables, each involving energy as a function of position or condition; of relevance here is the fluid potential of ground water (1).

Potential drop. Difference in total head between two equipotential lines (1).

Potentiometric surface. A surface that represents the level to which water will rise in tightly cased wells. If the head varies significantly with depth in the aquifer, then there may be more than one potentiometric surface. The water table is a particular potentiometric surface for an unconfined aquifer (3).

Pressure head. Hydrostatic pressure expressed as the height (above a measurement point) of a column of water that the pressure can support (1).

Pressure, static. Pressure exerted by a fluid at rest (1).

Public water supply system. System for provision to the public of piped water for human consumption, if such system has at least 15 service connections or regularly serves at least 25 individuals daily or at least 60 days out of the year. The term includes any collection, treatment, storage, and distribution facilities under control of the operator of such system and used primarily in connection with the system, and any collection or pretreatment storage facilities not under such control that are used primarily in connection with the system.

Pumping test. A test that is conducted to determine aquifer or well characteristics (1). A test made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer. A pump test may be used to determine the capacity of the well and the hydraulic characteristics of the aquifer. Also called aquifer test (3).

Radial flow. The flow of water in an aquifer toward a vertically oriented well (3).

Radius of influence. The radial distance from the center of a well bore to the point where there is no lowering of the water table or potentiometric surface (the edge of its cone of depression) (2).

Recharge (r). The addition of water to the zone of saturation; also, the amount of water added. Can be expressed as a rate (i.e., in/yr) or a volume (2).

Recharge area. Area in which water reaches the zone of saturation by surface infiltration (1). An area in which there are downward components of hydraulic head in the aquifer. Infiltration moves downward into the deeper parts of an aquifer in a recharge area (3).

Recharge basin. A basin or pit excavated to provide a means of allowing water to soak into the ground at rates exceeding those that would occur naturally (2).

Recharge boundary. An aquifer system boundary that adds water to the aquifer. Streams and lakes are typical recharge boundaries (2).

Runoff. That part of precipitation flowing to surface streams (1). The total amount of water flowing in a stream. It includes overland flow, return flow, interflow, and baseflow (2).

Saturated zone. Portion of the subsurface environment in which all voids are ideally filled with water under pressure greater than atmospheric (1). The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer (3). Also called the phreatic zone.

SDWA. Safe Drinking Water Act.

Semiconfined. An aquifer that has a "leaky" confining unit and displays characteristics of both confined and unconfined aquifers (see leaky aquifer) (1).

Sole Source Aquifer (SSA). An aquifer that is the sole or principal source of drinking water, as established under Section 1424(e) of the SDWA.

Solute transport. Net flux of solute through a hydrogeologic unit, controlled by the flow of subsurface water and transport mechanisms (1).

Solute transport model. Mathematical model used to predict the movement of solutes (generally contaminants) in an aquifer through time.

Solution channel. Tubular or planar channel formed by solution in carbonate-rock terrains, usually along joints and bedding planes (4).

Sorption. Processes that remove solutes from the fluid phase and concentrate them on the solid phase of a medium; used to encompass absorption and adsorption (1).

Specific discharge. The volume of water flowing through a unit cross-sectional area of an aquifer (1).

Specific yield. The ratio of the volume of water that a given mass of saturated rock or soil will yield by gravity to the volume of that mass. This ratio is stated as a percentage (1).

Spring. Discrete place where ground water flows naturally from rock or soil onto the land surface or into a surface-water body (1).

SSA. See Sole Source Aquifer.

Stagnation point. A place in a ground-water flow field at which the ground water is not moving. The magnitude of vectors of hydraulic head at the point are equal but opposite in direction (3).

Static head. See head, static.

State. Includes, in addition to the several States, only the District of Columbia, Guam, the Commonwealth of Puerto Rico, the Northern Mariana Islands, the Virgin Islands, American Samoa, and the Trust Territory of the Pacific Islands.

State Wellhead Protection Program. Program to protect wellhead protection areas within a State's jurisdiction from contaminants that may have any adverse effects on the health of persons (SDWA, subsection 1428(a)).

Static water level. The level of water in a well that is not being affected by withdrawal of ground water (2).

Storage coefficient. Volume of water an aquifer releases from or takes into storage per unit surface (or subsurface) area per unit change in head (1).

Storage, specific. The amount of water released from or taken into storage per unit volume of a porous medium per unit change in head (3).

Storativity (s). A dimensionless term representing the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to the specific yield. Also called storage coefficient (3).

Time of travel (TOT). The time required for a contaminant to move in the saturated zone from a specific point to a well.

TOT. See time of travel.

Transmissivity (t). Rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths (1). The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity values are given in gallons per minute through a vertical section of an aquifer 1 foot wide and extending the full saturated height of an aquifer under a hydraulic gradient of one in the English Engineering system; in the Standard International System, transmissivity is given in cubic meters per day through a vertical section of an aquifer 1 meter wide and extending the full saturated height of an aquifer under a hydraulic gradient of one (2). It is a function of properties of the liquid, the porous media, and the thickness of the porous media (3).

Transport. Conveyance of solutes and particles in flow systems (1).

Turbulent flow. Water flow in which the flow lines are confused and heterogeneously mixed. It is typical of flow in surface water bodies (2). That type of flow in which the fluid particles move along very irregular paths. Momentum can be exchanged between one portion of the fluid and another. Compare with laminar flow (3).

UIC. See Underground Injection Control.

Unconfined. Conditions in which the upper surface of the zone of saturation forms a water table under atmospheric pressure (1).

Unconsolidated aquifer. An aquifer made up of loose material, such as sand or gravel, that has not undergone lithification.

Underground Injection Control (UIC). The regulations for injection wells. The program provides grants to States under Section 1443(b) of SDWA.

Unsaturated flow. Movement of water in a porous medium in which the pore spaces are not filled with water (1).

Unsaturated zone. The zone between the land surface and the deepest or regional water table. It includes the root zone, intermediate zone, and capillary fringe. The pore spaces contain water, as well as air and other gases at less than atmospheric pressure. Saturated bodies, such as perched ground water, may exist in the unsaturated zone, and water pressure within these may be greater than atmospheric (1). Same as vadose zone.

Vadose zone. See unsaturated zone.

Velocity, average interstitial (v). Average rate of ground-water flow in interstices, expressed as the product of hydraulic conductivity and hydraulic gradient divided by the effective porosity. It is synonymous with average linear ground-water velocity or effective velocity (1).

Water budget. An evaluation of all the sources of supply and the corresponding discharges with respect to an aquifer or a drainage basin (3).

Water table. Upper surface of a zone of saturation, where that surface is not formed by a confining unit; water pressure in the porous medium is equal to atmospheric pressure (1). The surface between the vadose zone and the ground water; that surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere (2). The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric. It can be measured by installing shallow wells extending a few feet into the zone of saturation and then measuring the water level in those wells (3).

Well field. An area containing two or more wells supplying a public water supply system.

Wellfield. Synonymous with well field.

Well, fully penetrating. A well drilled to the bottom of an aquifer, constructed in such a way that it withdraws water from the entire thickness of the aquifer (3).

Wellhead. The physical structure, facility, or device at the land surface from or through which ground water flows or is pumped from subsurface, water-bearing formations.

Wellhead Protection Area (WHPA). The surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field.

Well interference. See interference.

Well screen. A filtering device used to keep sediment from entering a water well (2).

Well yield. The volume of water discharged from a well in gallons per minute or cubic meters per day (2).

WHPA. See Wellhead Protection Area.

ZOC. See zone of contribution.

ZOI. See zone of influence.

Zone of Contribution (ZOC). The area surrounding a pumping well that encompasses all areas or features that supply ground-water recharge to the well.

Zone of Influence (ZOI). The area surrounding a pumping well within which the water table or potentiometric surfaces have been changed due to ground-water withdrawal.

Zone of Transport (ZOT). The area surrounding a pumping well, bounded by an isochrone and/or isoconcentration contour, through which a contaminant may travel and reach the well.

ZOT. See zone of transport.

APPENDIX D

MODEL ASSESSMENT FOR DELINEATING WELL HEAD PROTECTION AREAS

Excerpt From Draft Report

Included in this appendix are an edited version of the Executive Summary and a list of models from this draft report, prepared by Paul K.M. van der Heijde and Milovan S. Beljin of the International Ground Water Modeling Center at the Holcomb Research Institute, at Butler Unviersity, Indianapolis, Indiana. This report was prepared at the request of the Office of Ground-Water Protection through a Cooperative Agreement between Holcomb Research Institute and the Office of Research and Development at EPA. Management of this effort was provided by the Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma. The final report will be available soon.

EXECUTIVE SUMMARY

One element of the 1986 Amendments to the Safe Drinking Water Act (SDWA) of 1974 is the protection of wellhead areas from contaminants that may have an adverse effect on public health. In establishing wellhead protection areas (WHPA's), many factors need to be considered, including:

- Zone of influence around a well or well field
- Presence of interfering neighboring wells or well fields
- Water table drawdown by the wells or well fields under consideration
- Various sources of contamination in the well recharge area (not necessarily the same as its zone of influence)
- Flow paths, transport velocities, and travel times for various contaminants under various hydrologic conditions.

To determine a site-specific WHPA, a systematic, analytic approach is necessary; mathematical simulation models provide a viable and often the only method to determine the WHPA when quantitative criteria are used. Such models are useful instruments in understanding the mechanisms of ground-water systems and the processes that influence their quality. Through their predictive capabilities, models provide a means to analyze the response of the site-specific system to various management alternatives and potential public health threats.

This report is aimed at providing information on existing ground-water flow and contaminant transport and fate models that might be considered for use in a WHPA delineation study. Although physical ground-water models can be useful for studying certain problems, the present focus is on mathematical flow and contaminant transport models in which the causal relationships among various components of the system and its environment are expressed in terms of mathematics and translated into a computer code.

Flow models are used to calculate changes in the distribution of hydraulic head of fluid pressure, drawdowns, rate and direction of flow, travel times, and the position of interfaces between immiscible fluids. Two types of models can be used to evaluate the chemical quality of ground water: hydrochemical models describing equilibrium reactions or reaction kinetics, and models that simulate solute transport and fate. Solute transport and fate models are used for the prediction of movement, concentrations, and mass balance components of water-soluble constituents.

The major criteria in selecting a model for a particular site-specific WHPA delineation are the model's suitability for the intended use, reliability, and efficient application. A model's efficiency is determined by the availability of its code and documentation, and its usability, portability, and modifiability. A perfect match rarely exists between desired characteristics and those of available models. Reassessment of the selection criteria and their relative weight is often necessary.

A major issue in model use is credibility, which is based on its proven reliability and the extent of its use. It is often assumed that most program errors originally present in a widely used program have been detected and corrected. Successful prior applications of a program in situations comparable to that for which it has been selected increase confidence in its applicability to the new situation.

A model's credibility can be evaluated in terms of the level of review and testing applied to it and by evaluating the success rate of its use. Testing a code involves two phases:

- Verification to check accuracy and assure that the code is fully operational,
- Field validation to determine how well the model's theoretical foundation describes the actual system behavior that the model has been designed to simulate.

Many of the available models have not been subjected to an extensive review and test procedure. Reviews have often been limited to peer review of theory and project reporting. Though most models have undergone some verification, the results of this are rarely reported, especially for the more complex models. Only a few models are reported to have undergone extensive field validation.

With respect to availability of ground-water software, a distinction can be made between public domain and proprietary software. Models that are available without restrictions in their use and distribution are considered to be in the public domain. Available proprietary software can be obtained or accessed under certain restrictions for use, duplication, and distribution.

SELECTED MODELS

Sixty-four models were selected a computerized search of the model annotation data bases of the International Ground Water Modeling Center (IGWMC). These data bases have been developed and maintained over the years with major support of EPA's

R.S. Kerr Environmental Research Laboratory in Ada, Oklahoma. This search was followed by an evaluation of the maintenance and update history of each model's code. Models were chosen because of their availability, level of documentation, and applicability to the wellhead protection zone delineation problem. Of the 64 models, 27 are flow and 37 are solute transport models. Fifty-one of the models are numerical and 13 are analytical and semi-analytical. The attachment below contains summary descriptions and detailed information on each model, and a comparison of usability and reliability characteristics.

A major limitation of this study is the lack of available data on model usability, reliability, and portability. Many models have not been subjected to the extensive evaluation required to rate them according to the criteria presented in this report. Additional activities to fill in the information gaps in this report are desirable.

Though adequate models are available for analysis of most flow-related problems, this is not the case for modeling contaminant transport. Accurate modeling of groundwater pollution is limited by some fundamental problems. Available numerical techniques are not always adequate for the most complex transport mechanisms. In addition, inadequate quantity or low quality of data often restricts model utility.

ATTACHMENT

DESCRIPTION OF MODEL CHARACTERISTICS

The "Model Output" column in the tabulation presented below contains the type of information available from the model output that could be required in WHPA delineation. The following abbreviations are used:

- AI Area of Influence (the area surrounding a pumping or recharging well within which the potentiometric surface has been changed).
- C Concentration (concentration map of contaminant throughout the simulated domain).
- CD Cone of Depression (the shape of the area of influence, in cross section).
- F Fluxes.
- P Pathways (path of a contaminant particle in the system).
- RA Recharge Area (the permeable layer through which precipitation and surface water may percolate to the aquifer and eventually reach the well).
- T Travel times (isochrones).
- V Velocities (ground-water velocities).

No.	Author(s)	Contact Address	Model Name (last update)	Model Description	Model Output	IGWMC Key
1.	S.P. Neuman P.A. Witherspoon	Dept. of Hydrology and Water Resources University of Arizona Tucson, AZ 85721	FREESURF I (1979)	Simulation of two-dimensional vertical or axisymmetric, steady-state flow in an anisotropic, heterogeneous, confined or water-table aquifer.	AI,CD,RA,F	0020
2.	S.P. Neuman	Dept. of Hydrology and Water Resources University of Arizona Tucson, AZ 85721	UNSAT2 (1979)	A two-dimensional finite element model for horizontal, vertical or axisymmetric simulation of transient flow in a variably saturated, nonuniform, anisotropic porous medium.	AI,CD,RA,F	0021
3.	T.N. Narasimhan	Battelle Pacific NW Lab Water and Land Resources Division P.O. Box 999 Richland, WA 99352	TRUST (1981)	To compute steady and nonsteady pressure head distributions in multidimensional, heterogeneous, variably saturated, deformable porous media with complex geometry.	AI,CD,RA,F	0120
4.	T.A. Prickett C.G. Lonnquist	Consulting Water Resources Engineers 6 G.H. Baker Drive Urbana, IL 61801	PLASM (1986)	A flexible two-dimensional or quasi-three-dimensional, transient, saturated flow model for single layer or multilayered confined, leaky confined, or water-table aquifer systems with optional evapotranspiration and recharge from streams.	AI,CD,RA,F	0322
5.	G.F. Pinder E.O. Frind	Dept. of Civil Engineering Princeton University Princeton, NJ 08540	ISOQUAD (1982)	Finite element model to simulate three-dimensional groundwater flow in confined and unconfined aquifers.	AI,CD,RA,F	0510
6.	G.F. Pinder C.I. Voss	U.S. Geological Survey Water Resources Division National Center,M.S.431 Reston, VA 22092	AQUIFEM (1979)	To simulate transient, areal ground water flow in an isotropic, heterogeneous, confined, leaky-confined or water table aquifer.	AI,CD,RA,F	0514
7.	P.S. Huyakorn	Geotrans, Inc. 209 Elden St., #301 Herndon, VA 22070	GREASE 2 (1982)	To study transient, multidimensional, saturated groundwater flow, solute and/or energy transport in fractured and unfractured, anisotropic, heterogeneous, multilayered porous media.	AI,CD,RA,F,C,V	0582
8.	P.S. Huyakorn	Geotrans, Inc. 209 Elden St., #301 Herndon, VA 22070	SATURN 2 (1982)	To study transient, two-dimensional variable saturated flow and solute transport in anisotropic, heterogeneous porous media.	AI,CD,RA,F,C,V	0583

No.	Author(s)	Contact Address	Model Name (last update)	Model Description	Model Output	IGWMC Key
9.	P. Huyakorn	Geotrans, Inc. 209 Elden St., #301 Herndon, VA 22070	SEFTRAN (1983)	To provide simple and cost-effective analyses of two-dimensional fluid flow and contaminant or heat transport problems in areal, cross-sectional or axisymmetric configuration of saturated, heterogeneous aquifers.	AI,CD,RA,F,C, V,P	0588
10.	P. Huyakorn	IGWMC Holcomb Research Institute Butler University 4600 Sunset Avenue Indianapolis, IN 46208	TRAFRAP (1986)	A finite element model to study transient, two dimensional, saturated ground water flow and chemical or radionuclide transport in fractured and unfractured, anisotropic, heterogeneous, multi-layered porous media.	AI,CD,RA,F,C, V,P	0589
11.	J.E. Reed M.S. Bedinger J.E. Terry	U.S. Geological Survey Room 2301 Federal Building 700 W. Capitol Ave. Little Rock, AR 72201	SUPERMOCK (1975)	To simulate transient stress and response in a saturated-unsaturated ground water flow system including a water-table aquifer overlying a confined aquifer.	AI,CD,RA	0611
12.	T.R. Knowles	Texas Water Development Board P.O. Box 13231 Austin, TX 78711	GWSIM-II (1981)	A transient, two-dimensional, horizontal model for prediction of water levels and water quality in an anisotropic heterogeneous confined and unconfined aquifer.	AI,CD,F,C,RA	0680
13.	INTERA Environmental Consultants, Inc. and INTERCOMP Resource Development & Eng., Inc.	U.S. Geological Survey Box 25046 Mail Stop 411 Denver Federal Center Lakewood, CO 80225	SWIP/ SWIPR/ SWENT (1985)	To simulate unsteady, three-dimensional groundwater flow, heat and contaminant transport in an anisotropic, heterogeneous aquifer.	AI,CD,RA,F,C, V	0692
14.	C.R. Faust T. Chan B.S. Ramada B.M. Thompson	Performance Assessment Dept. Office of Nuclear Waste Isolation Battelle Project Mngmt. Div. 505 King Avenue Columbus, OH 43201	STFLO (1982)	A linear finite element code for simulation of steady-state, two-dimensional (areal or vertical) plane or axisymmetric ground-water flow in anisotropic, heterogeneous, confined, leaky or water-table aquifers.	AI,CD,RA,F	0694
15.	L.F. Konikow J.D. Bredehoeft	U.S. Geological Survey 431 National Center Reston, VA 22092	MOC (1987)	To simulate transient, two-dimensional, horizontal groundwater flow and solute transport in confined, semiconfined or water table aquifers.	AI,CD,RA,F,C, V	0740

No.	Author(s)	Contact Address	Model Name (last update)	Model Description	Model Output	IGWMC Key
16.	S.P. Garabedian L.F. Konikow	U.S. Geological Survey 431 National Center Reston, VA 22092	FRONTRACK (1983)	A finite difference model for simulation of convective transport of a conservative tracer dissolved in groundwater under steady or transient flow conditions. The model calculates heads, velocities and tracer particle positions.	AI,CD,RA,F,C, V,P,T	0741
17.	W.E. Sanford L.F. Konikow	U.S. Geological Survey 431 National Center Reston, VA 22092	MOCDENSE (1986)	A model to simulate transport and dispersion of either one or two constituents in groundwater where there is two-dimensional, density dependent flow. It uses finite-difference and method of characteristics to solve the flow and transport equations.	AI,CD,RA,F,C, V	0742
18.	P.C. Trescott S.P. Larson	U.S. Geological Survey Branch of Groundwater M.S. 411 National Center Reston, VA 22092	USGS-3D- FLOW (1982)	To simulate transient, three-dimensional and quasi three-dimensional, saturated flow in anisotropic, heterogeneous ground water systems.	AI,CD,RA,F	0770
19.	P.C. Trescott G.F. Pinder S.P. Larson	U.S. Geological Survey Branch of Ground Water M.S. 411 National Center Reston, VA 22092	USGS-2D- FLOW (1976)	To simulate transient, two-dimensional horizontal or vertical flow in an anisotropic and hetrogeneous, confined, leaky-confined or water-table aquifer.	AI,CD,RA,F	0771
20.	Miller, I. J. Marion- Lambert	Golder Associates 2950 Northup Way Bellevue, WA 98004	GGWP (1983)	Steady-state or transient simulation of two-dimensional, vertical or axisymmetric and quasi-three dimensional flow and transport of reactive solutes in anisotropic, heterogeneous, multi-layered aquifer systems.	AI,CD,RA,F,C, V,P,T	1010
21.	G. Segol E.O. Frind	Dept. of Earth Sciences University of Waterloo Waterloo, Ontario Canada N2L 3G1	3-D SATURATED- UNSATURATED TRANSPORT MODEL (1976)	Determination of concentration of conservative or nonconservative solute in transient, three-dimensional saturated-unsaturated flow systems.	AI,CD,F,C	1070
22.	K.R. Rushton L.M. Tomlinson	Dept. of Civil Engineering Univ. of Birmingham P.O. Box 363 Birmingham, B15 2TT United Kingdom	AQU-1 (1979)	Basic transient model for single layered two-dimensional horizontal ground water flow.	AI,CD,F	1230
23.	H.M. Haitjema O.D.L. Strack	School of Public & Environmental Affairs 10th Street Indiana University Bloomington, IN 47405	SYLENS (1985)	Modeling of steady-state groundwater flow in regional double aquifer systems with local interconnections.	AI,CD,RA,F	1791

No.	Author(s)	Contact Address	Model Name (last update)	Model Description	Model Output	IGWMC Key
24.	C. Van Den Akker	National Institute for Water Supply P.O. Box 150 2260 Ad Leidschendam The Netherlands	FLOP-2 (1975)	To generate pathlines for steady-state, flow in a semi-confined, isotropic, homogeneous aquifer without storage and to calculate residence times for a number of water particles.	C,V,P,T	1821
25.	P. Van der Veer	Rijkswaterstaat Data Processing Division P.O. Box 5809 2280 HV Rijswijk (2.H.) The Netherlands	MOTGRO (1981)	Prediction of groundwater head and stream function for two-dimensional, vertical, steady and unsteady, single or multiple fluid flow in inhomogeneous, anisotropic, confined or unconfined aquifers of arbitrary shapes.	AI,CD,F,V,P,T	1830
26.	S.K. Gupta C.T. Kincaid P.R. Meyer C.A. Newbill C.R. Cole	Battelle Pacific NW Labs P.O. Box 999 Richland, WA 99352	CFEST (1985)	A three-dimensional finite element model to simulate coupled transient flow, solute- and heat-transport in saturated porous media.	AI,CD,F,RA,C,V	2070
27.	S.K. Gupta C.R. Cole F.W. Bond	Battelle Pacific NW Labs Water and Land Resources Division P.O. Box 999 Richland, WA 99352	FE3DGW (1985)	Transient or steady state, three-dimensional simulation of flow in a large multi-layered groundwater basin.	AI,CD,RA,F,V	2072
28.	A.E. Reisenauer C.R. Cole	Water and Land Resources Division Battelle Pacific NW Labs P.O. Box 999 Richland, WA 99352	VTT (1979)	A transient model to calculate hydraulic head in confined-unconfined multi-layered aquifer systems, and to generate streamlines and travel-times.	AI,CD,V,P,T	2092
29.	R.W. Nelson	Battelle Pacific NW Labs Sigma 5 Building P.O. Box 999 Richland, WA 99352	PATHS (1983)	To evaluate contamination problems in transient, two-dimensional, horizontal, groundwater flow systems using an analytical solution for the flow equation and a numerical solution for the pathline equations.	F,V,C,P,T	2120
30.	R.D. Schmidt	U.S. Dept. of the Interior Bureau of Mines P.O. Box 1660 Twin Cities, MN 55111	ISL-50 (1979)	A three-dimensional model to describe transient flow behaviour of leachants and groundwater in an anisotropic, homogeneous aquifer involving an arbitrary pattern of injection and recovery wells.	V,P,T	2560
31.	L.R. Townley J.L. Wilson A.S. Costa	Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics Room 48-211 Massachusetts Inst. of Technology Cambridge, MA 02139	AQUIFEM-1 (1979)	A two-dimensional, finite-element model for transient, horizontal groundwater flow.	AI,CD,RA,F	2630

No.	Author(s)	Contact Address	Model Name (last update)	Model Description	Model Output	IGWMC Key
60.	D. Koch	Koch & Associates 1660 S. Fillmore St. Denver, CO 80210	AQUIFER4 (1984)	A radial finite difference model to simulate transient three-dimensional groundwater flow in a leaky-confined aquifer.	AI,CD,F	6305
61.	INTERA Environmental Consultants	Battelle Project Management Division Performance Assessment Dept. Office of Nuclear Waste Isolation 505 King Avenue Columbus, OH 43201	VERTPAK-1 (1982)	A package of analytical solutions assembled to assist in verification of numerical codes used to simulate fluid flow, rock deformation, and solute transport in fractured and unfractured porous media.	C,V,T	6340
62.	W.C. Walton	IGWMC Holcomb Research Institute Butler University 4600 Sunset Avenue Indianapolis, IN 46208	35 MICRO-COMPUTER PROGRAMS (1984)	A series of analytical and simple numerical programs to analyze flow and transport of solutes and heat in confined, leaky or water table aquifers with simple geometry.	AI,CD,C,V,T	6350
63.	M.S. Beljin	IGWMC Holcomb Research Institute Butler University 4600 Sunset Avenue Indianapolis, IN 46208	SOLUTE (1985)	A package of 8 analytical models for solute transport simulation in groundwater. The package also includes programs for unit conversion and error function calculation.	C,T	6380
64.	T. Steenhuis S. Pacenka	Northeast Regional Agricultural Engineering Service Riley-Robb Hall Cornell University Ithaca, NY 14853	MOUSE (1987)	A set of four linked models for tracking the movement and fate of a soluble chemical in saturated and unsaturated zones.	C,T	6390

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